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This report results from a contract tasking IP Pavlov Institute of Physiology as follows: The contractor will perform a psychoacoustical investigation of the effects of different angles of head position, and a comparison of the subject perception of approaching and receding with monaural and binaural signal presentation.

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TECHNICAL REPORT

"PERCEPTION BY OPERATORS OF APPROACH AND WITHDRAWAL OF MOVING SOUND SOURCES (AUDITORY IMAGES)"

Project number SPC 98 4006
contract number F61775-98-WE081

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INTRODUCTION

From many reviews on directional hearing (e.g. Altman, 1983; Middlebrooks and Green, 1991; Grantham, 1995; Wightman and Kistler, 1997) it can be seen that the problem of localization of approaching or withdrawing sound sources is still remained practically unstudied. As is known, perception of sounds produced by approaching or withdrawing sound sources is determined by changes in amplitude and frequency spectrum of the acoustic wave at the point of observation. Changes of signal spectrum are of importance for estimation of the sound source distance below 3 m and above 15 m (Coleman, 1963). The distance perception depends on spectrum range of the sound signal and on the sound source size (Blauert, 1974). At short distances the changes are result from the interaction of the incident sound wave with the head, torso and external ears. These changes are significant for sound frequencies above 1.5 kHz. At distances above 15 m, intensity of the high-frequency part of sound spectrum is decreased with sound source withdrawal. The higher is sound frequency, the greater is decrease of the high-frequency part of the spectrum with increase of the sound source distance (Piercy et al., 1977). In accordance with these data, with the sound source distance above 15 m, amplitude increase of low-frequency components of the signal spectrum produce sensation of approach of the sound source, whereas amplitude decrease results in sensation of the sound source withdrawal (Bekesy, 1960).

Attenuation of sound with distance, generally referred to as the (1/R) loss, is expressed as

$$(1/R)\ \text{loss (in dB)} = 20\log_{10}(R/R_0), \qquad (1)$$

or

$$P = k/R_0 \qquad (2)$$

where R and Ro are the distances from sound source to some point and to the observation point, respectively, P is the sound pressure at the observation point, and k is a proportionality coefficient (Coleman, 1963). It follows that, under free-field conditions, sound pressure loss increases by 6 dB with every doubling of the distance from the observation point to the sound source.

The above changes of the acoustical signal at the point of observation following distance change can be utilized by a listener for estimation of the sound source distance and parameters of its movement.

For static sound sources, sound loss is the most general of the cues to distance, obtaining for all types of sounds and at different distances. Sound intensity change which produced a sensation of distance increase for two times, amounted to 9-30 dB and differred significantly from calculated values (Stevens and Guirao, 1962; Warren, 1968; Gardner, 1969; Mershon and King, 1975; Petersen, 1990; Begault, 1991). According to different authors, differential intensity threshold for pure tones is equal to 0.5-2 dB at the intensity level from 20 to 60 dB SL (e.g. Florentine et al., 1993). Differential sensitivity for noise intensity is near to 4 dB at sound intensity levels above 20 dB SL (Miller, 1947). These data can be used for estimation of the minimal (1/R) value which can be perceived by the listener. If differential threshold value is assumed as equal to 0.8 dB, then distance changes for 10 % (R/Ro=1.1) should be perceived by the listener. It was shown that differential thresholds for distance judgement of wide-band noise were equal to 3-7% of the standard value at distances above 6 m and increased up to 20% at shorter distances (Strybel and Perrott, 1984).

High perfomance in differentiation between the distances of static sound sources does not mean the possibility of precise estimation of the distance absolute value. This is confirmed by the following experiments. Sound signals of equal intensity at the point of observation were presented to the listeners through a set of loudspeakers placed at distances of 1.5-8 m from the observer. The listeners estimated the sounds as coming from the nearest loudspeaker, irrespective of position of the loudspeaker which was really sounding (Coleman, 1962; Gardner, 1968, 1969. With presentation of sounds of different intensities, the sounds of higher intensity were perceived as nearer, and the less intensive sounds were perceived as more distant (Gardner, 1969; Litovsky and Clifton, 1992).

When the subjects were asked to estimate the distance to the sound source in meters, scattering of their responses proved great, but the values of the mean estimate sistematically lowered with increase of the distance (Laws, 1973). The estimates did not show pronounced dependence on the actual position of the sound source . Thus, intensity change is a cue of distance change, but it can not be the basis for absolute estimation of a distance (Meyer, 1927).

Measuring sound intensity near the ear of the listener showed that its change with time is nearly exponential. This is conditioned by the fact that sound intensity is in inverse ratio to square of the distance. With sound source approaching to the observer, sound intensty changes gradually at first, and then increases rapidly. Thus at short distances from the listener to the sound source, intensity changes are more pronounced than at farer distances. It is shown that though intensity change at the point of observation depends on sound source intensity, intensity ratio to its change over time does not depend on sound source intensity (Shaw, McGowan, and Turvey, 1991).

Discrimination ability of the auditory system in relation to distance to the source of wide-band sound signals was measured with the procedure of two-interval forced choice (Ashmead, LeRoy, and Odom, 1990). Estimation of sound source distance depended on sound signal intensity even at distances of 1-2 m. It is shown that with subject moving toward sound source, its intensity is an absolute cue of the distance change under free-field conditions (Ashmead, Davis, and Northington, 1995). Sound pressure change with distance in relation to distance was determined by the authors as

$$(dP/P)/dr=(dP/dr)/P=-(kr^{-2})/(kr^{-1})=-r^{-1} \qquad (3)$$

where P is pressure, r is sound source distance, and k is a coeficient. This estimate does not depend on sound initial intensity level and can provide for absolute estimation of the distance change. Experiments performed by Ashmead, Davis, and Nortington (1995) confirmed this possibility. In the first experimental series the subjects, in a static position, estimated a distance (5-20 m) to a source of the noise signal of 1.5 s duration. In the second series the noise signal was initiated when the subjects were moving in the direction of the noise source. Sound intensity was randomly changed so that it could not be a cue of distance. It was shown that noise signal perception during listener movement essentially improved absolute estimation of the distance change.

Basing on the equation (3) it is possible to estimate sound pressure change over time when sound source is moving with a constant velocity. Under uniform motion of the sound source, sound pressure over time will change as follows:

$$(dP/dt)/P=(dP/dr)(dr/dt)/P=-(kr^{-2})v/(kr^{-1})=-r^{-1}v=-(t^{-1}v^{-1})v=-t^{-1} \quad (4)$$

where t is time, P is sound pressure, r is a distance to the sound source, v is velocity of the uniform motion. Thus sound pressure change is inversly related to motion time.

In experiments by Hellman (1997) it was shown that when sound signal pressure was linearly changed over time, subjects estimated them as approaching with the same success as they estimated really approaching sound source. In these experiments white noise records were used with different sound pressure changes over time. The sounds were listened to through the earphones.

An approach was also elaborated in this laboratory which allowed to simulate frontal approach and withdrawal of a sound source with the help of two loudspeakers fixing initial and ending points of the trajectory of the simulated motion of the auditory image (Pack and Ogorodnikova, 1994 a, 1994 b, 1997). The auditory image perceived by the subject moved between two sound sources as if it were a actual motion of the sound source. Auditory image approach and withdrawal were achieved through amplitude change of the signal at two loudspeakers with identical characteristics: the signal amplitude linearly increased at the near loudspeaker and correspondingly decreased at the far one (auditory image approach) or vice versa (auditory image withdrawal). Sound signals were trains of impulses of 100 μs duration. Signal duration was changed by variation of the impulse repetition rate. Change of signal duration, under fixed distance between the loudspeakers, resulted in change of the auditory image movement velocity. At different velocities of the auditory image approach (1-8 m/s) the motion was estimated by subjects as uniform in 79% of cases. In 14% of cases the motion was perceived as accelerated, and in 7% of cases the subjects experienced difficulties with estimation. Change in the repetition rate allowed to model accelerated motion. At accelerations of 0.03-0.08 m/s2 accelerated motion was perceived by subjects in half of all cases, independently on movement velocity (1, 2, or 4 m/s).

Investigations of radial movement delt mostly with frontal approach or withdrawal of the auditory image. Meanwhile, it is possible that at different azimuthal angles, binaural mechanisms of perception of the auditory image approach and withdrawal will manifest themselves to a different extent.

Involvement of the binaural mechanisms and acoustic effects of the external ears in distance judgements were not studied in detail; it was only mentioned that they can be employed under near-field conditions. Effect of binaural differences arising with plane acoustical wave is called acoustical parallax. Acoustical parallax will be of maximal value with movement along the interaural axis. Binaural and pinna cues were studied mostly in conditions of lateral motion in horizontal plane (from left to right or vice versa). Minimal duration of sound signal necessary for perception of lateral movement in horizontal plane is about 80-150 ms (Blauert, 1972; Viskov, 1975).

As to radial movement, it is still unknown a minimal duration of the sound signal which was needed for correct determination of direction of the image movement at different azimuthal angles. Also, there is no data on differential thresholds for velocity which are an essential characteristic of discriminative ability of the auditory system for localization of moving sound sources.

The main task of the present work was to determine differential thresholds for velocity with the auditory image approach and withdrawal at different azimuthal angles.

METHODS

Subjects

The main part of the investigations was fulfilled on six subjects (three men and three women) with normal hearing, aging 25-36. The subjects were trained to listen to the sounds beforehand. In a part of the work six patients (two men and four women aged 17-42) suffering from unilateral deafness of sensorineural origin took place. Subject’s audiograms were obtained using a standard audiometer MA-31.

Experimental room

The measurements were performed in a sound-attenuated chamber with volume of 62.2 cubic metres. The ceiling, floor, and walls of the chamber were covered with a special material eliminating reverberation inside the chamber (Appendix). Attenuation of external noises inside the chamber exceeded 40 dB within the range from 500 to 16000 Hz .

Signals modelling approach and withdrawal of the auditory image

In the present work the above mentioned modelling approach is used (Pak and Ogorodnikova, 1997) with some modifications. Trains of wide-band noise burst (20-20000 Hz) are used as stimulus. The wide-band noise was produced by a random number generator. Burst duration was 41 ms, repetition period was 50 ms. At this repetition rate the fused motion of the auditory image is perceived (Altman a. Viskov, 1977; Kozevnikova, 1980; Vartanian, Rosenblum et al., 1981). Signal duration could be changed through change of a number of bursts in the train and varied from 91 to 1391 ms. Structure of the signals fed to the loudspeakers is shown on Fig. 1. Acoustical signal modelling approach and withdrawal of the auditory image was created due to linearly changing amplitude of the signal at two loudspeakers with identical characteristics. To produce sensation of approaching auditory image, signal amplitude increased gradually at the near loudspeaker and decreased at the far loudspeaker. To produce sensation of withdrawing image, signal amplitude increased at the far loudspeaker and decreased at the near one. Maximal to minimal ratio of the signal intensities amounted to 38.6 dB at the near loudspeaker and to 39.1 dB at the far one. The difference in maximal and minimal intensities was chosen on the basis of preliminary listenings as well as on the basis of the data by Pak and Ogorodnikova (1997). Minimal sound intensity levels at both loudspeakers were the same. Maximal sound intensity at the point of listening amounted to about 69 dB SPL.

Acoustical signals emitted from the near and far loudspeakers as well as the resulting signal obtained with simultaneous sounding of both loudspeakers and producing sensation of a moving sound are shown on Fig. 2. Dynamic spectrum of the resulting signal recorded with a microphone at the place of the subject's head is shown on Fig. 3.

Change of signal duration (under conditions of constant distance between the sound sources) results in changing velocity of the auditory image movement. Change of the burst repetition rate throughout the signal gives the possibility to model accelerated movement of the auditory image.

Signal duration as well as velocity of the auditory image movement were changed by variation of number bursts in the train; this allowed to have unchanged spectrum for signals of different duration. The step of changing was 50 ms. Differential thresholds of movement velocity were measured with changing of the signal duration by 1-ms step.

Signal generation software.

Signal generation was produced with the help of special program QSYNTH which provided generation of signals that can play from two channels. Signals designed in the program was saved in format RIFF Wave with default extension,“wav” . Saved files were read by signal processing application and played with the help of the D/A - sound board (SB-16) with dynamic range 60 dB.

Parameters of burst trains were set independently for each channel. Application allow to specify burst duration, interburst interval, number of bursts, initial and final burst amplitudes, and delay between two channels . Signals were generated with linear amplitude change over time (Fig. 1).Signals were presented randomly with time interval 5s.

Study design

Signals were led from the computer output to the amplifier "Brig" and then to two dynamic loudspeakers (25AC327) which were placed in a sound-attenuated chamber at distances of 1.1 and 4.5 m from the subject, at the level of his/her head.

Subject's report was made using a panel with buttons which was in the subject's hand. Pressing the button resulted in flash of one of the electric bulbs of a signlling device which was situated outside the chamber, before the experimenter.

Bruel & Kjaer apparatus (microphone 4145, preamplifier 2629 and amplifier 2606) was used to measure sound intensity at the place of subject's head location, as well as to calibrate loudspeakers and to measure spectral characteristics of sound signals. Spectral analysis was performed with the help of interface CED-1401plus and PC "Pentium". This device provides sampling rate up to 12500 Hz and signal spectrum within the frequency range up to 62500 Hz. Dynamic spectra and changing in time acoustic signals were obtained with the help of program Watefull.

Calibration of loudspeakers

To calibrate the loudspeakers a measuring microphone was placed at the place of listener's head location. The distances from the microphone to the near and far loudspeakers was 1.1 and 4.5 m, respectively. Acoustical measurements were made with equal level of the electrical signal at the near and far loudspeakers.

Procedure

A. Determinaton of minimal signal duration for radial motion perception by healthy subjects

Six subjects with normal hearing were asked to listen to sound signals delivered at different angles to the head and body. The following angles between the head-and-body position and direction of the simulated movement were employed: 0, 30, 45, 60, and 90 degrees. Body position of the subject was maintained due to a steady armchair with head rest. The head position was fixed via gaze fixation at a certain point marked at the wall of the chamber at the eyes level. The procedure of three-alternaitive choice was used. The subject had to press one of three buttons in response to one of three perceived situations: a) the auditory image is approaching; b) it is withdrawing; c) it is not moving. Before the experiments the subject was trained to use the buttons without looking at them, i.e. without moving the body or eyes toward the panel with buttons. Subject's responses were registered by the experimenter outside the chamber.

Sound signals were randomly presented in five series, each series (for one azimuthal angle) included signals of different durations and movement directions (approach and withdrawal). Signal durations were 91, 141, 191, 291, 391, 491, and 791 ms. During one experimental series each signal was presented for ten times with 5-s interval between signals; altogether 140 signals were presented during a 12-min series. Time interval between series lasted for about 6 min. Duration of the whole session including training and five experimental series amounted to 1 hour 40 min. 5 sessions, each with five experimental series, were fulfilled on each subject.

B. Determination of minimal signal duration for radial motion perception by patients with unilateral deafness

In general the pocedure was the same as with healthy subjects. However the investigation was performed in two sessions, each of two hours duration. The sessions were performed on different days. The following azimuthal angles were employed: 0, 30, 45, 60, 90, -30, -45,-60. and -90 degrees. During the first session the subjects were presented with sounds from the side of the damaged ear. During the second session the sounds were presented from the side of normally hearing ear. One subject (Subj. 6, BO) was investigated only form the side of the damaged ear. At the beginning of the session the subject was instructed about the procedure in detail, and a test listening was done with 15-20 signals of different movement directions and different durations. For the most of patients signal durations were higher than in experiments with healthy subjects and amounted to 291, 391, 491,791, 991, 1191, and 1391 ms. The range of durations depended on results of the first session and could be changed for the second session depending on succesfulness of recognition by the patient of the direction of the auditory image motion. Each experimental series included presentation of signals of one azimuthal angle and of both directions (approach and withdrawal) of the auditory image motion, with the above durations of sounding. The first and the final series were fulfilled with 0-degree azimuthal angle.

C. Measurement of differential thresholds for velocity with auditory image radial movement

Six healthy subjects took part in these experiments. Differential thresholds for velocity with approach and withdrawal of the auditory image were measured at three azimuthal angles: 0, 45, and 90 degrees. Three values of movement velocity were used: 3.43, 4.92, and 6.92 m/s. Movement velocity (V) was calculated as

$$V=S/T,$$

where S is the distance between the loudspeakers, and T is duration of signal. With constant value of the distance between the loudspeakers of 3.4 m, the above velocity values were obtained at signal durations of 0.491, 0.691, and 0.991 s.

Standard and test signals were presented in pair, with time interval of 450 ms between them. Time structure of the standard was as described above: bursts of 41 ms duration, 9 ms time interval between successive bursts in the train, and repetition period 50 ms. Duration of standard signals was 491, 691, and 991 ms and their velocity amounted to 3.43, 4.92, and 6.92 m/s. Altogether six standard signals were used: with three velocities and two directions of movement (approach and withdrawal). Velocity of the test signal could be changed within the range of +/- 30% of the standard velocity. Velocity of the auditory image movement was changed through change in signal duration. To change test signal velocity within the range mentioned above, burst duration was changed within 25-56 ms. With fixed interburst interval (9 ms) the period of burst presentation in the test signals was equal to 34-65 ms. Change of burst duration for 1 ms resulted in velocity change for 2% in comparison with velocity of the standard signal. For each of six standard signals 30 test signals were constructed.

When measuring differential thresolds for velocity a procedure of three-alternative forced choice was employed. The subject was offered with three versions of possible responses concerning movement velocity of the second auditory image: 1) the velocity is higher, 2) equal, 3) it is lower than velocity of the first auditory image motion. The subject's response consisted in pressing one of three buttons and the response was registered. Threshold measurements were performed with the help of the adaptive procedure (Levitt, 1971). Initial difference between velocities of the standard and test stimuli amounted to 30%. This value was decreased first with the step of 4% untill the response "equal" was obtained. After preliminary estimation of the differential threshold the step of the velocity change was decreased to 2%. Threshold value was crossed four-six times. Minimal difference in signal velocities recognized by the subject in more than 2/3 of cases was taken for threshold. Differential thresholds for velocities higher than those of standard signal and for velocities lower than those were measured separately in order to make easier velocity estimation by the subject. During the final data processing the both values of the differential threshold were averaged.

Threshold measurement at a given velocity and direction of the auditory image motion lasted for about 10 min. During this time the subject was presented with 50-70 pairs of signals. Differential thresholds at one direction of movement (approach or withdrawal) were measured during two hours, then was a break not shorter than 30 min, and afterwards measurements were done with the other direction of movement. Altogether five such experimental series were fulfilled with each subject.

Data processing

Minimal signal duration (MD) necessary for motion recognition by healthy subjects was determined in two ways: 1) as duration corresponding to 25% of responses "not moving" and 2) as duration corresponding to 75% of correct estimations of motion direction. To obtain mean values of MD, the results were averaged over 600 responses from six subjects obtained in 30 experimental sessions with listening to signals of a certain duration and a certain azimuthal angle. When estimating response probability, confidence intervals were determined with the help of binomial distribution; standard error for correct estimations did not exceed 2%. For each subject the data of five experimental sessions were averaged and functions relating probability of responses "does not move" to signal duration were constructed. Functions relating probability of correct responses to signal duration were costructed as well.

The data obtained on patients with unilateral deafness were processed in the same way, except for a criterion taken for MD estimation. Unlike healthy subjects, correct responses in patients usually amounted to 70-80% even at long stimulus durations. Therefore a 65%-criterion was used for MD estimation with correct responses and a 35%-criterion was taken to estimate MD with responses "not moving". With single listening to signal series, standard error for estimation of percent of correct responses did not exceed 11%.

The data on velocity differential threshols were processed with multifactor analysis of variences (MANOVA). Mean values and standard error were calculated for velocity differential thresholds. Veber ratio ($\Delta V/V$) was detemined with the help of linear regression anlysis.

RESULTS

A. Minimal duration (MD) of the sound signal for radial motion perception by healthy subjects

Psychometric functions

Method of three-alternative choice was used to measure MD by percent of responses "not moving" and by percent of responses with correct estimation of movement direction.

It was found that in all the subjects, increase in signal duration resulted in a decrease of probability of responses "not moving" and in an increase of probability of correct estimations of the auditory image movement direction (Fig. 4). It can be seen that for signal durations of 391, 491, and 791 ms percent of responses "not moving" does not exceed 5%; meanwhile, percent of correct responses is higher than 85%. Within the interval from 91 to 291 ms, responses of both types could be observed. In some cases psychometric functions obtained at azimuthal angle of 90 degrees were more sloping than at other azimuthal angles (e.g. in Subject 3 on Fig. 4). This was true both for responses "not moving" and for correct estimations of motion direction.

Individual differences

Certain differences in psychometric functions were observed in different subjects with estimation of imitated radial movement of the auditory image (Fig. 4). In subjects 2, 4, 5, 6 a rather low percent of responses "not moving" was observed: percent of these responses did not exceed 50% even at short stimulus durations; at the same time percent of correct estimations of movement direction was rather high in these subects. Meanwhile two other subjects (NN 1 and 3 on Fig. 4) estimated short signals mainly as unmoving.

MD values needed for movement detection and for differentiation between its directions were the same at most of the azimuthal angles in subjects 1, 2, 3. In subjects 4, 5, 6 MD values needed for movement detection were lower than those needed for differentiaton between movement directions (Fig. 4).

Effects of the azimuthal angle

The above psychometric functions obtained at different azimuthal angles are presented on Fig. 5.1 as averaged over six subjects. It can be seen that at azimuthal angles 0, 30, 45, and 60 degrees, minimal signal duration needed for motion detection was rather near and corresponded to about 141 ms stimulus duration (with 25% of responses "not moving"). At these azimuthal angles, minimal duration necessary for movement direction determination corresponded to about 191 ms signal duration (with 75% of correct responses). A somewhat different results were obtained at 90-deg azimuth: the function was more sloping and shifted to the right, i.e. to higher values of signal durations. At this azimuthal angle MD needed for motion detection corresponded to about 191 ms stimulus duration, and MD needed for correct estimation of movement direction corresponded to about 291 ms stimulus duration. Thus, according to two different criteria, at 90-deg azimuth the above psychometric functions differred from functions obtained at other azimuthal angles (Fig. 5.2).

B. Minimal duration (MD) of the sound signal for radial motion perception by patients with unilateral deafness

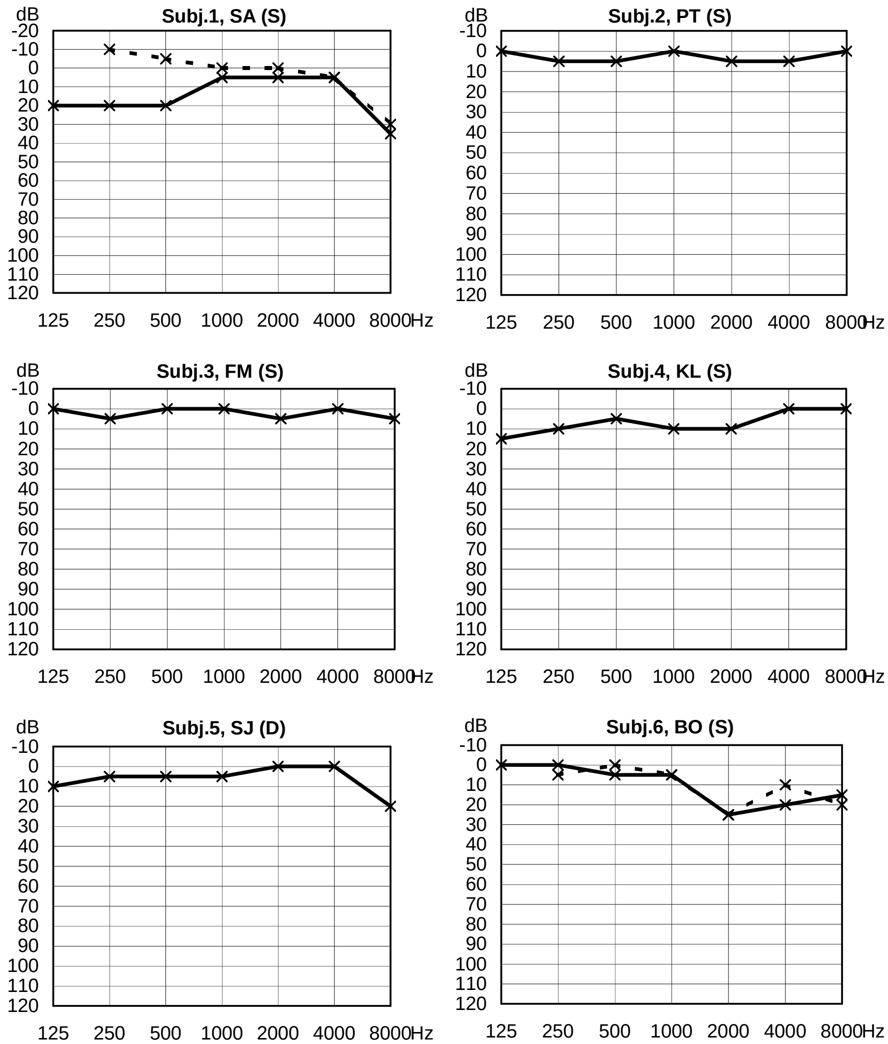
Characteristic of the patients with full unilateral deafness is shown on Table 1. In all the patients hearing loss at the impaired ear exceeded 110 dB.

Table 1.

Subjects, sex	Age	Audiometric frequencies (in Hz) with hearing loss exceeded 15 dB	Side, and etiology of unilateral deafness
SA, m	31	S, 125-500, 8000 (35 dB)	D, cochlear haemorrhage, 41.5 years ago
PT, f	28	S, no	D, following parotitis in childhood
FM, m	17	S, no	D, probably following parotitis in childhood
KL, f	42	S, 125	D, cochlear hemorrhage 45 years ago
JS, f	32	D, 8000 (20 dB)	S, following parotitis in childhood
BO, f	25	S, 2000-8000 (15 dB)	D, probably following parotitis in childhood

Notes: Figures in brackets mean hearing loss at 8000 Hz.

Audiograms for the patients' hearing ears are presented below.



In patients with full unilateral deafness psychometic functions for motion detection and estimation of movement direction (Figs. 6, 7) differed significantly from the functions obtained in subjects with normal hearing (Figs. 4, 5). Besides, these functions were significantly different in different patients.

Subjects SA and KL, with similar etiology of deafness (Table 1), perceived the most signals as unmoving. Even at signal durations above 1 s, percent of responses "not moving" could achieve only 40-50%. Minimal duration for motion detection in these subjects lay within the range from 291 to 691 ms (Fig. 8). Probability of correct estimation of movement direction usually did not exceed a 90%-level in these subjects (Figs. 6,7) these functions were rather sloping in subjects SA and KL. In subject SA, with 35-dB hearing loss at 8000 Hz, an increase in minimal duration for movement detection was observed with increase of the azimuthal angle beyond 45 degrees at both sides from the frontal position (Fig. 8). In subject KL the observed MD variations with azimuth change did not exceed the step value of signal duration change and could be connected with a relatively low precision of the measurements (N=20). Control series with repeated presentations of signals of the same azimuth value (Figs. 10-11) showed rather great variation in estimations of this subject.

In anamnesis of four other subjects there was putative or verified parotitis. They all became deaf in childhood. These subjects were characterized by high percent of correct estimation of movement direction: in many cases 90-100% level of correct responses was achieved (Figs. 6, 7, subjects 2, 3, 5, 6). Besides, in these subjects at signal duration long enough, a low percent (below 5%) of responses "not moving" was observed.

In two subjects (FM and BO) MDs needed for movement detection and for movement direction recognition were practically the same (compare Figs. 8 and 9). These subjects estimated correctly movement direction even at short signal durations. Differences in MD values at different azimuthal angles did not excceed the step in duration variations and were of random character. It could be concluded that in these cases MDs did not depend on azimuthal direction.

In subject PT, MDs for movement detection (91-141 ms, Fig. 8) were lower than those for correct estimation of movement direction (291-791, Fig. 9). Especially long durations were needed at azimuthal angles of 30 and 45 degrees (Fig. 9). It can not be excluded however that this difference was the result of the order of signal presentation (with a gradual increase of the azimuthal angle) and insufficient training of this subject in listening to the signals. As shows Fig. 10, with results of repeated series with the only azimuthal angle of 0 degrees, successive measurements could give rather different results in this subject.

In majority of cases an improvement in signal discrimination was observed in repeated testings (Figs. 10-11). Meanwhile, subject JS was the exception of this rule: as shown on Figs. 7 and 11, results obtained in this subject were extremely stable over the whole course of the investigation, as compared with results obtained in other subjects. However even this subject showed rather high valeus of MDs as measured in repeated testings at 0-degrees azimuthal angle: MD for motion detection amounted to about 400 ms (vs. 141 ms in healthy subjects, Fig. 5) and MD needed for correct estimation of the movement direction was also close to 400 ms (vs. 191 ms in healthy subjects, Fig. 5). A special feature of this subject was slight but definite increase in MD values at azimuthal angles from 45 to 90 degrees at the side of hearing ear - both for movement detection (Fig. 8) and for correct estimation of movement direction (Fig. 9). Perhaps these results were connected with 20-dB hearing loss at 8000 Hz in this subject, as it was also the case in subject 1, with 35-dB hearing loss at 8000 Hz. It should be noted that in other subjects there were no hearing loss at 8000 Hz, except for subject 6, with 15 dB hearing loss at 8000 Hz (Table 1).

C. Differential thresholds for velocity of the approach and withdrawal auditory image

Differential thresholds for velocity in repeated testings

With the help of two-way MANOVA, velocity differential thresholds (for approach and withdrawal combined) were compared depending on the number of succesive experimental session and on the subjects' individual properties. The value of the differential threshold decreased in repeated testings: $F(4, 1075)=12.16$, $p<0.001$. The first testing gave the mean differential threshold value of 0.80 m/s, which lowered to 0.58 m/s at the third testing (Fig. 12.1). In subsequent measurements this value somewhat rose again - to 0.67-0.63ms. Thus even in trained listeners a 20% variations in mean differential thresholds could be observed in repeated testings.

Considering interaction between of subject performance and number of the experimental testing ($F(20, 1060)=5.92$, $p<0.0001$) shown that mean threshold value obtained for subject SA in the second testing differed significantly from all other values ($p<0.0001$; Fig 12.2). Therefore results of the second testing for subject SA were excluded from the following consideration.

Velocity differential thresholds for approach and withdrawal of the auditory image

Differential thresholds were compared with three-way MANOVA depending on velocity, movement direction, and azimuth. There were no significant differences in differential thresholds vor velocity with auditory image approach and withdrawal ($F[1, 1041]=0.993$). When considering direction and azimuth as factors, no differences in differential threshold values were revealed as well ($F[2, 1041]=0.465$). Certain differences were revealed with estimation of interaction between factors velocity and direction ($F[2, 1038]=3.47$, $p<0.05$). With movement velocity 3.43 m/s, differential thresholds for approach and withdrawal differed for 0.09 m/s

($p<0.05$), however at higher velocities (4.62 and 6.92 m/s) the difference was insignificant (Fig. 13).

Velocity differential thresholds at different velocities

Differential thresholds were compared with three-waytor MANOVA depending on velocity, subject performance, and azimuth. Velocity differential threshold value changed depending on velocity value ($F[2, 1041]=189.34$, $p<0.001$). After averaging the data obtained on six subjects a regression analysus was used (Fig. 14.1). The relative differential threshold ($\Delta V/V$), as averaged over movement directions, subject group, and azimuthal angles, was practically constant and equal to about 13%.

Velocity differential thresholds at different azimuthal angles

Differential thresholds were compared with three-factor MANOVA depending on velocity, subject subject performance, and azimuth. Velocity differential thresholds showed no significant dependance on azimuth ($F[2, 1041]=1.35$). Consideration of interaction between velocity and azimuth factors also did not reveal significant differences in velocity differential thresholds ($F[4, 1039]=0.442$).

Fig. 15 shows relative (top) and absolute (bottom) differential thresholds in relation to motion velocity at different azimuthal angles (with averaging over subjects and motion directions).

Individual differences in velocity differential threshold values

Differential velocity thresholds were different in different subjects ($F[5, 1069]=36.58$, $p<0.001$). Mean values lay within the range from 0.53 to 0.96m/s (Fig. 16).

Individual values of differential velocity thresholds are shown on Fig. 14.2. These data (averaged over azimuthal angles and movement directions) were used for determination of coefficients of linear regression equation (Table 2). As can be seen from the Table, individual values of relative differential threshold lay within 8-21%.

Table 2

Subjects	Regression line	R^2
SA	y=0.21x-0.19	0.9989
PT	y=0.14x-0.09	0.9997
FM	y=0.08x+0.18	0.9963
KL	y=0.10x+0.22	0.8875
JS	y=0.12x+0.08	0.9840
BO	y=0.13x-0.12	0.9934

Differences were also found with analysis of interaction between factors subject and movement direction ($F[5, 1032]=4.80$, $p<0.001$). Differential thresholds were different with auditory image approach and withdrawal in two subjects (1 and 6): in these subjects, with auditory image approach, differential threshold values were higher than with withdrawal for 0.21 and 0.18 m/s, respectively ($p<0.03$).

Figs. 17 and 18 show differential velocity thresholds for six subjects at different velocities and different azimuthal angles of the auditory image movement. As can be seen from Fig. 17, with velocity increase from 3.43 to 6.92 m/s, differential velocity threshold rose in all the subjects though to a different extent. The increase in differential velocity threshold following velocity increase lay within 0.28-0.74 m/s.

In four subjects (SA, FM, JS, BO) there were no significant differences in differential velocity thresholds at three azimuthal angles studied (Fig. 18) . In subject PT differential threshold at 0-degree azimuth proved lower for 0.11 m/s than at 45-degree azimuth and for 0.16 m/s as compared with 90-degree azimuth ($p<0.05$). On the contrary, in subject KL differential threshold at 0-degree azimuth was higher for 0.21 and 0,16 m/s as compared with its values at 45 and 90 degrees respectively ($p<0.04$). In all six subjects there were no significant differences for differential thresholds at 45- and 90-degree azimuths (Fig.18). To illustrate individual differences, Fig. 19 shows mean values of differential thresholds, standard deviations, and standard errors for all six subjects, obtained at different velocities and azimuths of the auditory image movement.

Control experiments

Experiment 1. In this experiment differential velocity thresholds were measured for approaching auditory image in conditions of changing stimulus velocity by changing a number of noise bursts in signal. Repetition period of bursts in trains was 50, 35 and 25 ms for velocities 3.43, 4.62, and 6.92 m/s respectively which provided optimal step of velocity change. The measurements were performed with Subject SA. The data of this experiment was compared with data, obtained from the main study, in which velocity changes were provided by changing noise burst duration. No significant differences were found in differential velocity thresholds measured in these two ways (Fig. 20, top).

Experiment 2. The aim of this experiment was to evaluate a possible relationship between the velocity differential thresholds and differential thresholds for signal duration. The main question was whether the velocity discrimination ability was based on detection of change in signal duration? For this purpose in one of the subjects (KL) differential thresholds for duration were measured with signals which were noise burst trains with parameters described in the main experiment except for the amplitude envelope: the amplitude of the signals was not changed over signal duration, i.e. there was no apparent auditory movement. Differential thresholds for duration were measured with the adaptive procedure (just as described in the main experiment for velocity differential thresholds), at 0-degree azimuth. It proved that with increase in signal duration, relative differential thresholds for duration rose, whereas velocity differential thresholds in the same interval of signal duration remained constant (Fig. 20, bottom).

DISCUSSION

A special feature of the present study of movement perception was the method of three-alternative choice, unlike two-alternative forced choice method employed in majority of the previous investigations which employed the task of a choice either between two directions of movement (Harris and Sergeant, 1971; Perrott and Tucker, 1988; Strybel and Neal, 1994) or between stationary and moving sound sources or auditory images (Perrott and Musikant, 1977; Strybel and Neale, 1994). The method of three-alternative choice allowed to obtained in the same experiment the data concerning both detection of the radial movement and differentiation between its directions (approach or withdrawal).

A. Radial motion perception by healthy subjects

It seems of importance to compare results obtained in the present work with those in literature concerning minimal observation time necessary for movement detection (over different coordinates of the three-dimensional space) and determination of its direction.

Minimal duration (MD) of the sound signal needed for radial movement detection at azimuthal angles from 0 to 60 degrees (about 140 ms) was close to values obtained for lateral movement in the horizontal plane as well as for elevation in the vertical plane: in a great number of studies MD threshold value within about 100-150 ms was found - both for free-field and dichotic conditions of stimulation (Viskov, 1975; Perrott and Musikant, 1977; Strybel et al., 1989; Sabery and Perrott, 1990; Strybel et al., 1992; Strybel and Neal, 1994). Thus MD threshold values for auditory image motion detection over all three coordinates proved rather similar.

It should be noted that there is one more criterion which allows to judge indirectly about critical time necessary to evoke movement sensation. This criterion is minimal time interval between successive bursts in the train perceived as moving auditory image. As it was shown for the auditory image lateral movement in the horizontal plane this critical time interval was about 100-150 ms (Viskov, 1975;Altman and Viskov, 1977). This value, which secured fused sensation of the auditory image movement, was near to MD, obtained in the present work.

One more observation seems of principal importance. As it was described above, minimal durations for radial movement detection and for differentiation beween its directions (approach and withdrawal) were correspondingly about 140 and 190 ms at azimuthal angles of 0-60 degrees. Meanwhile, at azimuthal angle of 90 degrees minimal duration values needed both for movement detection (about 190 ms) and for correct recognition of its direction (about 290 ms) proved higher than at other azimuthal angles. This evidences an increase of the inertial process of the brain mechanisms at this azimuthal angle. On the other hand, it is known that 90-degree azimuth is an area of the lowest differentiation ability of sound localization in the horizontal plane (Blauert, 1974; Makous, Middlebrooks, 1990; Middlebrooks, Green, 1991). It is not clear however if this fact is connected with inertia increase of the brain mechanisms in the process of radial motion detection at 90-degree azimuth. Possible role and share of these two factors (minimal localization sensitivity and large errors at azimuthal angle of 90 degrees) are planned to be studied in further investigations.

B. Radial motion perception by patients with full unilateral deafness

Unlike the data obtained on subjects with normal hearing, the data for patients with full unilateal deafness of sensorineural origin varied greatly in different patients. In subjects SA and KL the MD-values were so high that did not allow to exclude a possibility of involvement of head scanning movements, as well as of changing the time constant of temporal integration in auditory perception. A possibility of increase of the time constant of the central integration process in the above two subjects is in agreement with their clinical histories: in Subj. SA the hemorrhage to the cochlea was the result of the brain trauma, and in Subj. KL there was an stroke in anamnesis.

Data obtained on subjects PT, JS, and BO with full unilateral deafness corresponded to the data by Vartanian and Chernigovskaya (1980) with modelling radial movement by means of amplitude change of the signal in the single sound source. Thus it may be supposed that in these subjects movement detection and differentiation between its directions could be secured on the basis of such sign as direction of the signal amplitude change in time.

Subject FM (the youngest) showed rather low MD-values, near to those obtained on healthy subjects. It seems that time constant of the integration process was low in this subject.

Unlike healthy subjects, no pronounced MD-dependence on azimuthal angle was observed. Only two subjects (SA and JS) with pronounced hearing loss in high-frequency region (Table 1) showed a tendency for increase of MD-values with increase of the azimuthal angle. This shows to an important role of high-frequency components of the signal spectrum in localization of moving auditory image, in particular also with movement over radial coordinate.

A great variabilty of the results obtained in patients with full unilateral deafness is in ageement with the data by Slattery and Middlebrooks (1994) with sound localization in horizontal plane obtained on patients with full unilateral deafness.

C. Velocity differential thresholds

In the model of radial movement used in this work no pronounced dependance of velocity relative differential threshold on movement velocity or azimuth value was found (Fig. 15). Differences observed in two subjects were of opposite direction (Fig. 18) and thus could not influence the general result. The value of differential threshold is in good agreement with the data obtained with modelling approach of the auditory image by means of amplitude modulated impulse train ($A \sim t^2$) delivered through a stationary loudspeaker (Altman, 1983). Our control measurements aimed at comparison of relative differential thresholds for movement velocity and for signal duration (Fig. 20, bottom) do not exclude a possibility of velocity estimation mainly through signal duration.

CONCLUSION

The main results obtained in this study concerning perception of the radial movement of the auditory image can be summarized as follows:

1. To detect radial movement of the auditory image a minimal duration (MD) of the sound signal is necessary which amounted to about 140 ms at on the average at azimuthal angles of 0-60 degrees, and to about 190 ms at 90-degree azimuth (Figs. 4, 5).

2. To differentiate correctly between approach and withdrawal of the moving auditory image a minimal duration of the sound signal of about 190 ms was needed on the average at azimuthal angles of 0-60 degrees and of about 290 ms at the azimuthal angle of 90 degrees (Figs. 4, 5).

3. In patients with full unilateral deafness the above values of minimal signal duration necessary for movement detection and for differentiation between approach and withdrawal were usually significantly higher, though to a different extent in different subjects. Besides, variability of responses in the majority of patients was also significantly higher than in subjects with normal hearing (Figs. 6-11). MD-values showed no pronounced dependance on azimuth (Figs. 8-9).

4. Differential velocity thresholds were measured at velocties of the auditory image movement from 3.43 to 6.92 m/s and showed an increase from about 0.47 to 0.95 m/s on the

average with the velocity increase. Mean value of the relative differential threshold was near to 13% at all velocities used (Figs. 13-15).

5. Mean values of differential velocity thresholds lowered over repeated experimental sessions from about 0.8 to about 0.6 m/s (Fig.12).

6. Differential velocity thresholds showed dependence on movement direction (approach or withdrawal) only at the lowest velocity value of 3.43 m/s (Fig.13).

7. Differential velocity thresholds did not depend on azimuthal angle of the auditory image movement (Fig. 15).

8. Individual differences in differential velocity thresholds were found in relation to velocity and azimuth of the auditory image movement (Figs. 17-19).

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LEGENDS TO FIGURES

Fig. 1. Schematic structure of signals simulating auditory image motion from the far loudspeaker to the near one. I: signal emitted by the far loudspeaker, II: from the near one. T, signal duration. t, impulse duration. t_1, pause. A_1, amplitude of the first impulse in the train. A_2, amplitude of the last impulse.

Fig. 2. Oscillograms of the signals emitted by the near loudspeaker (1), by the far one (2), and a total result (3) at the place of the listener's head (perceived by listeners as approaching auditory image).

Fig. 3. Dynamic spectrum of the acoustical signal at the place of the listener's head.

Fig. 4. Percent of correct direction judgements (1) and motionless judgements (2) as a function of sound duration at different azimuthal angles. The data for six subjects: 1 - SA, 2 -PT, 3 - FM, 4 - KL, 5 - JS, 6 - BO). N=100. On the abscissa: signal duration in milliseconds.

Fig. 5. Top (1): percent of correct direction judgements and motionless judgements as a function of sound duration at different azimuthal angles. Mean data for six subjects. N=600. Designations as on Fig 4. Bottom (2): Minimum signal duration needed for motion detection (circles) and for recognition of movement direction (dots) as a function of the azimuth. Mean data for six subjects.

Fig. 6. Percent of motionless judgements (left) and correct direction judgments (right) as a function of sound duration at different azimuthal angles. Individual data for three patients with full unilateral deafness. N=20. On the abscissa: signal duration, in milliseconds.

Fig. 7. Percent of motionless judgements (left) and correct direction judgements (right) as a function of sound duration at different azimuthal angle. Individual data for three patients with full unilateral deafness. N=20. On the abscissa: signal duration, in milliseconds.

Fig. 8. Minimal signal durations needed for the auditory image motion detection at different azimuthal angles (polar axes). Individual data for six patients with full unilateral deafness. On the radial axes: minimal signal duration, in milliseconds. Positive angles (in degrees) correspond to right-side position of the loudspeakers, negative values correspond to left-side position.

Fig. 9. Minimal signal durations needed for correct recognition of movement direction at different azimuthal angles (polar axes). Individual data for six patients with full unilateral deafness. On the radial axes: minimal signal duration, in milliseconds. Positive angles (in degrees) correspond to right-side position of the loudspeakers, negative values correspond to left-side position.

Fig. 10. Percent of motionless judgements (left) and correct direction judgements (right) as a function of signal duration at 0-degree azimuthal angle. Individual data for three patients with full unilateral deafness. The data obtained in different experimental series are shown with different symbols. N=20. On the abscissa: signal duration, in milliseconds.

Fig. 11. Percent of motionless judgements (left) and correct direction judgements (right) as a function of signal duration at 0-degree azimuthal angle. Individual data for three patients with full unilateral deafness. Symbols: the data obtained in different experimental series. N=20. On the abscissa: signal duration, in milliseconds.

Fig.12. Differential velocity thresholds as a function of the testing number.

Top (1): the data averaged over six subjects, azimuth, velocity, and direction values (N=216). Bottom (2): individual data for six subjects (1-6, N=36). Vertical bars note standard errors.

Fig. 13. Differential velocity thresholds as a function of velocity of the auditory image approach and withdrawal. Mean data for six subjects, averaged over all azimuth values. N=180. Vertical bars note standard errors.

Fig. 14. Differential velocity thresholds as a function of movement velocity. Top (1): averaged data over six subjects, direction, and azimuth values (N=346). Bottom (2): individual data for six subjects (1-6; N=60). On the abscissa: signal movement velocity, in m/s. Solid lines show linear regression. Vertical bars note standard errors.

Fig. 15. Relative (1) and absolute (2) differential velocity thresholds in relation to velocity of the auditory image movement at different azimuthal angles. Averaged data over six subjects and two directions of movement. N=120. Vertical bars note standard errors.

Fig. 16. Individual differential velocity thresholds for six subjects (1-6). Mean data, averaged over direction, velovitiy, and azimuthal angle of the auditory image movement. N=180.

Fig. 17. Differential velocity thresholds for different subjects (1-6) at different velocity values. Mean data averaged over azimuths and and directions of the auditory image movement. N=60. Vertical bars note standard errors.

Fig. 18. Individual differential velocity thresholds for six subjects (1-6) as a function of azimuth. Mean data averaged over direction and velocity values. N=60. Vetical bars note standard errors.

Fig. 19. Differential velocity thresholds for different subjects at different velocities and azimuths of the auditory image movement. Mean data averaged over directions (approach and withdrawal) of the auditory image movement. N=20.

Fig. 20. Results of control experiments. Top: differential velocity thresholds measured by two methods, with velocity change at the cost of impulse duration (circles) and at the cost of impulse number (dots). The data for Subj. SA. Bottom: relative differential thresholds for velocity (dots) and for duration (circles) in relation to signal duration and to corresponding velocity values. The data for Subj. KL.

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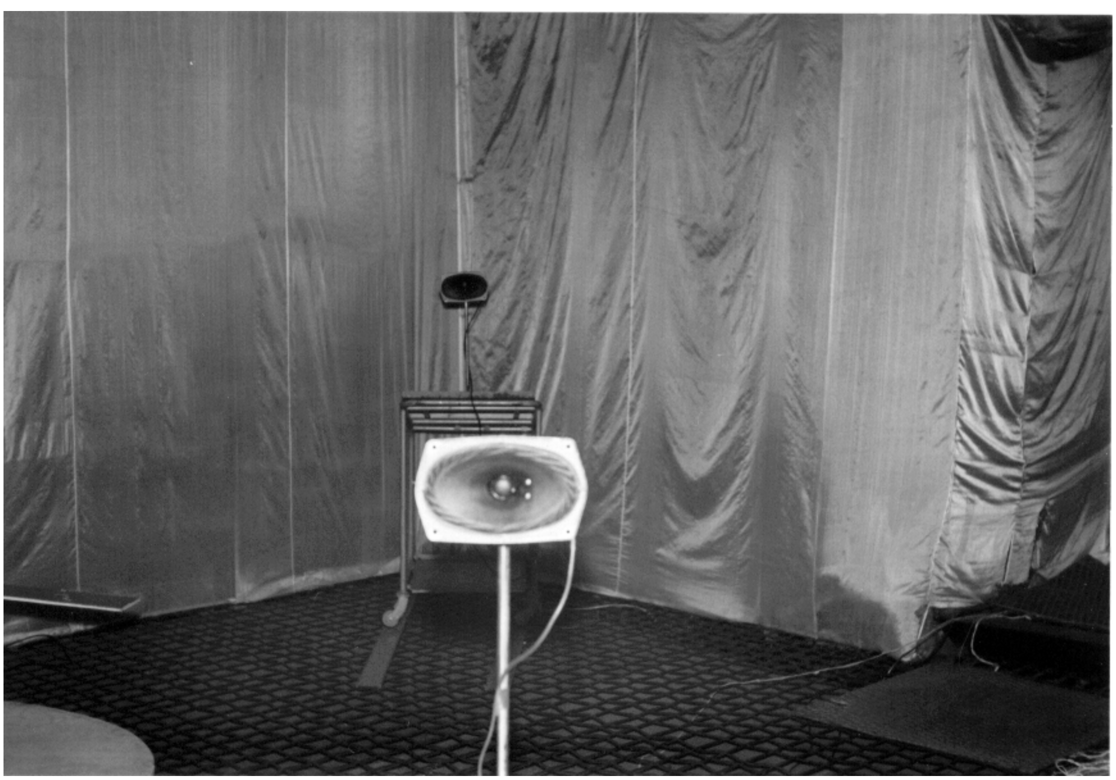
Appendix

General view of the experimental chamber



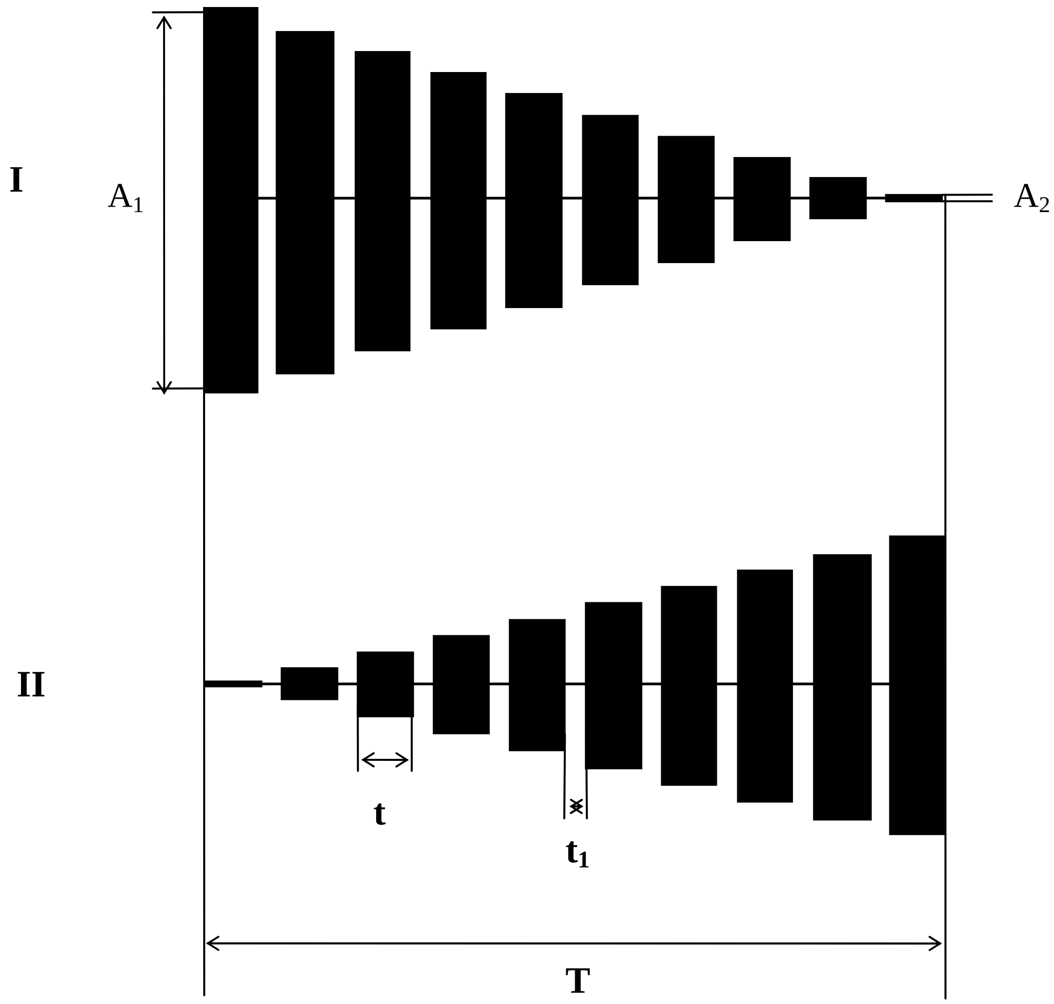


Fig. 1.

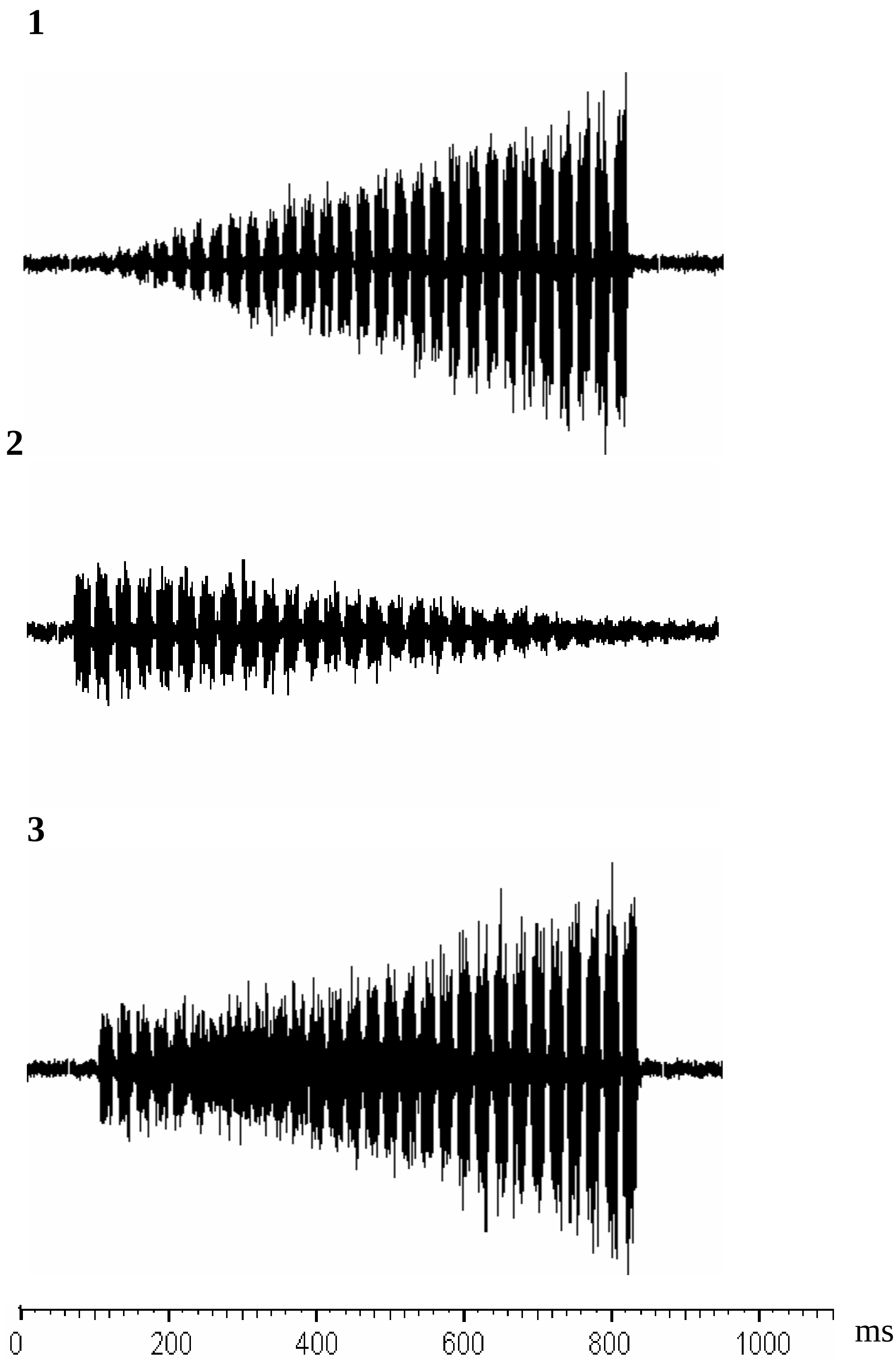


Fig. 2

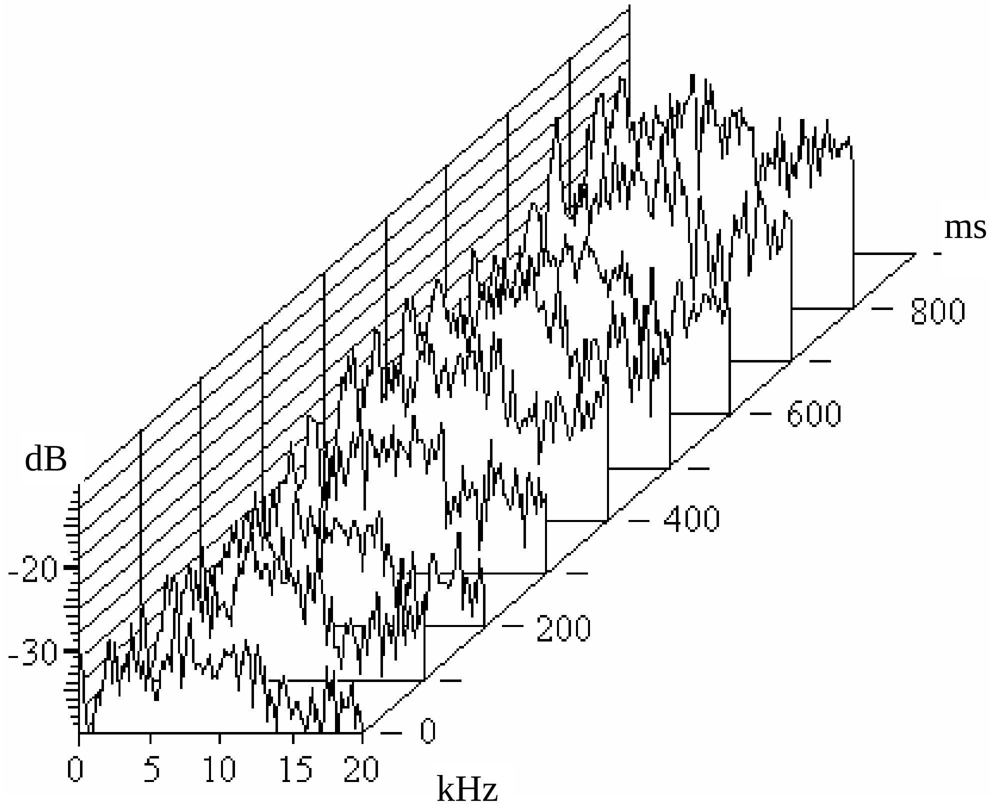
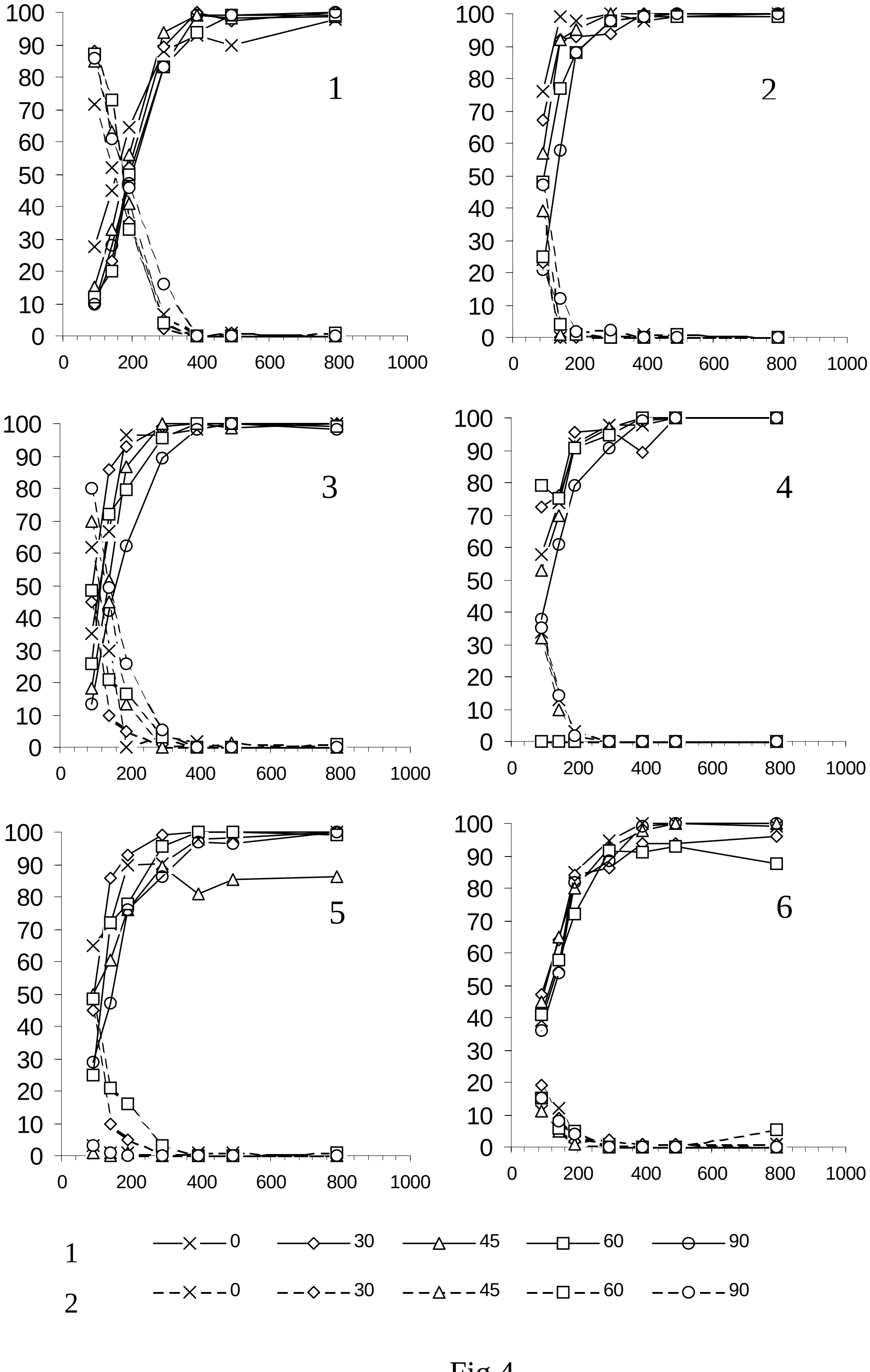


Fig. 3



1
2
3
4
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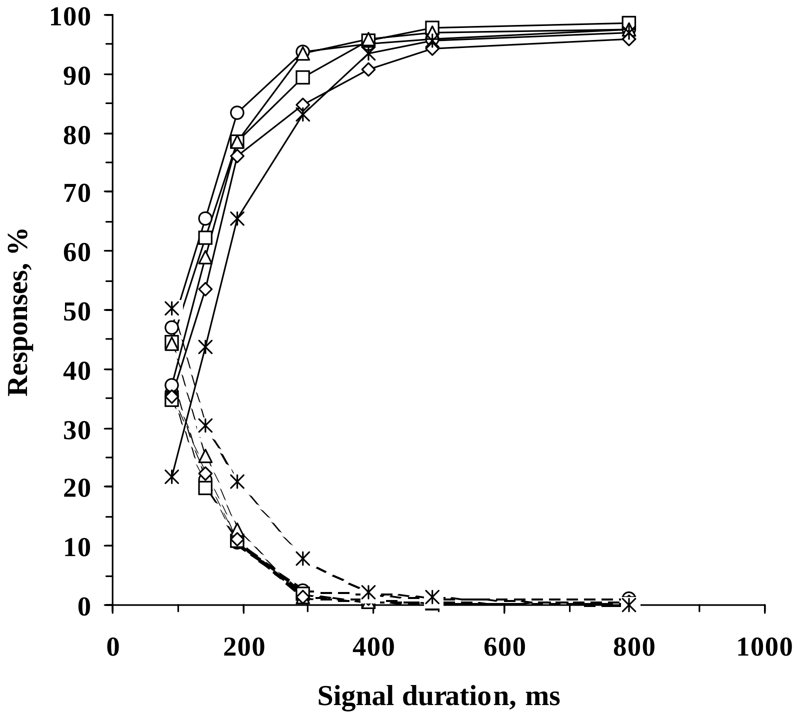
60
90

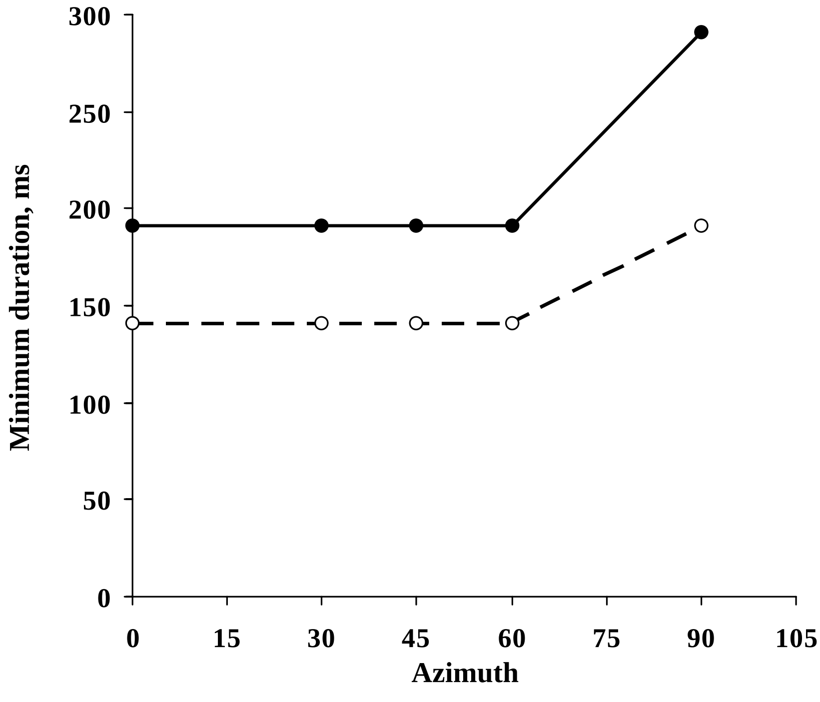
Fig.4.

1



100
90
80
70
60
50
40
30
20
10
0
Responses, %
0
200
400
600
800
1000
Signal duration, ms

2



300
250
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150
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Minimum duration, ms
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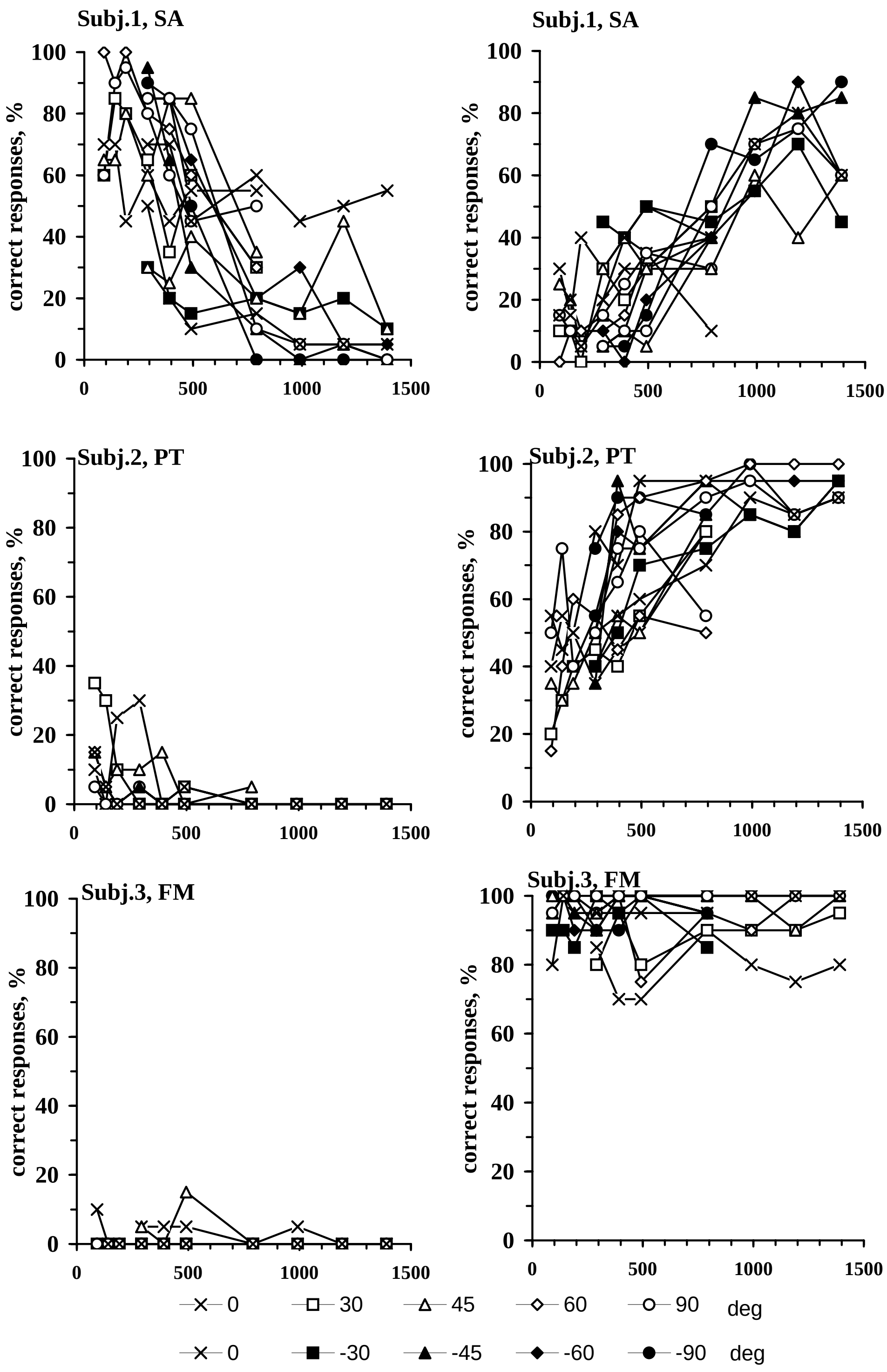
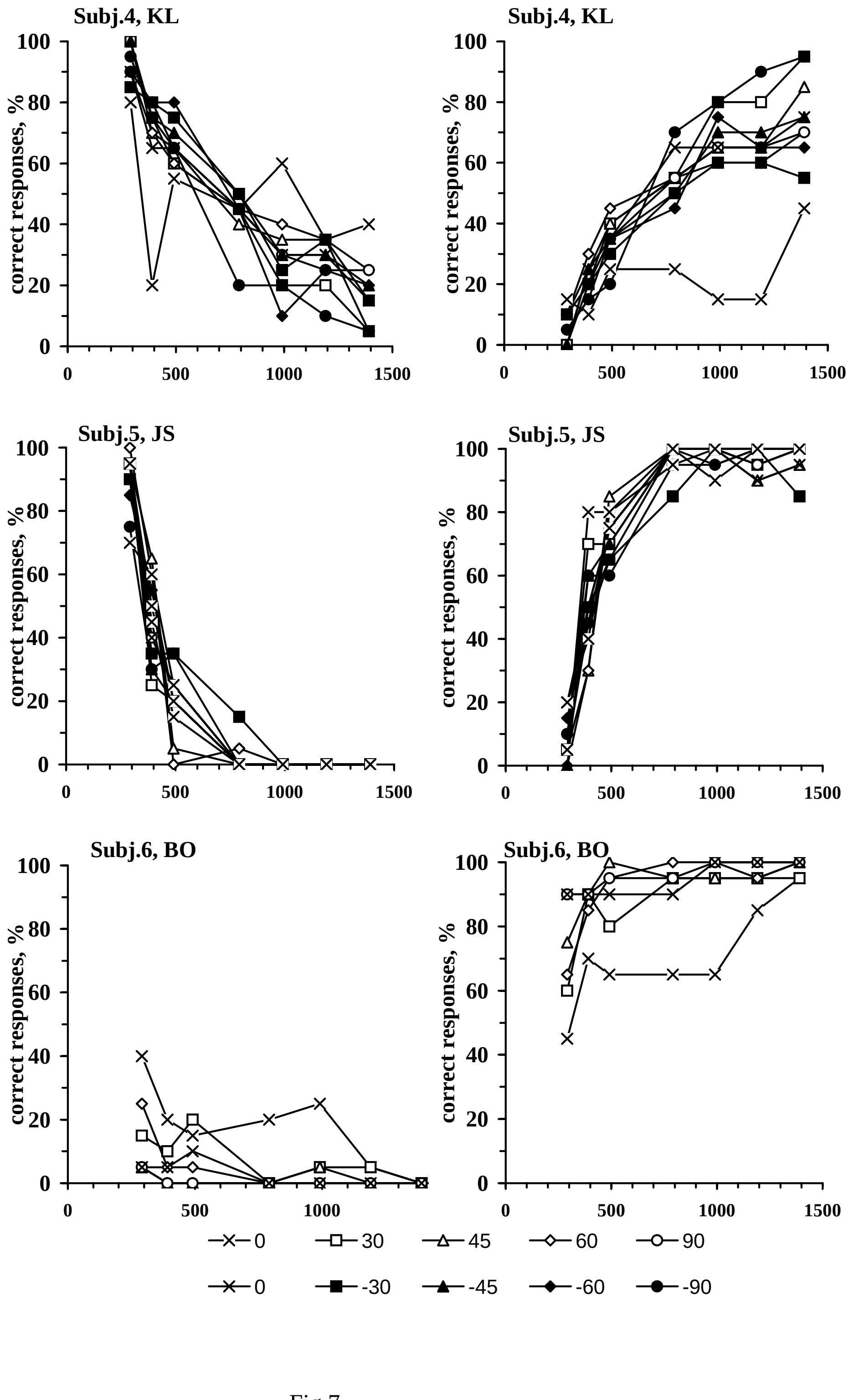
15
30
45
60
75
90
105
Azimuth

Fig.5



Subj.1, SA
correct responses, %
Subj.1, SA
correct responses, %
Subj.2, PT
correct responses, %
Subj.2, PT
correct responses, %
Subj.3, FM
correct responses, %
Subj.3, FM
correct responses, %
0 30 45 60 90 deg
0 -30 -45 -60 -90 deg

Fig.6


Subj.4, KL
correct responses, %
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80
60
40
20
0
0
500
1000
1500
Subj.4, KL
correct responses, %
Subj.5, JS
correct responses, %
Subj.5, JS
correct responses, %
Subj.6, BO
correct responses, %
Subj.6, BO
correct responses, %
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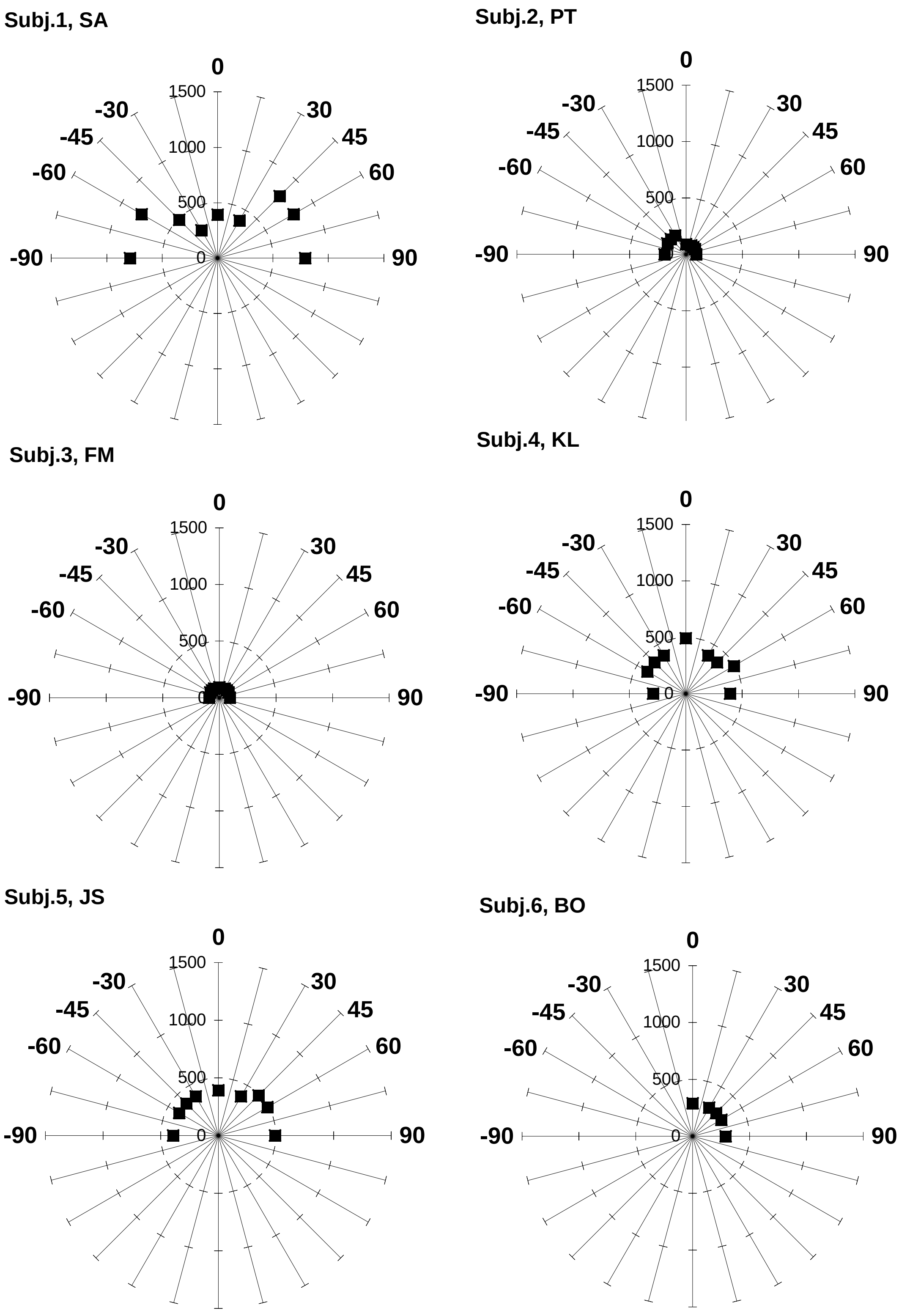
30
45
60
90
0
-30
-45
-60
-90

Fig.7


Subj.1, SA
Subj.2, PT
Subj.3, FM
Subj.4, KL
Subj.5, JS
Subj.6, BO
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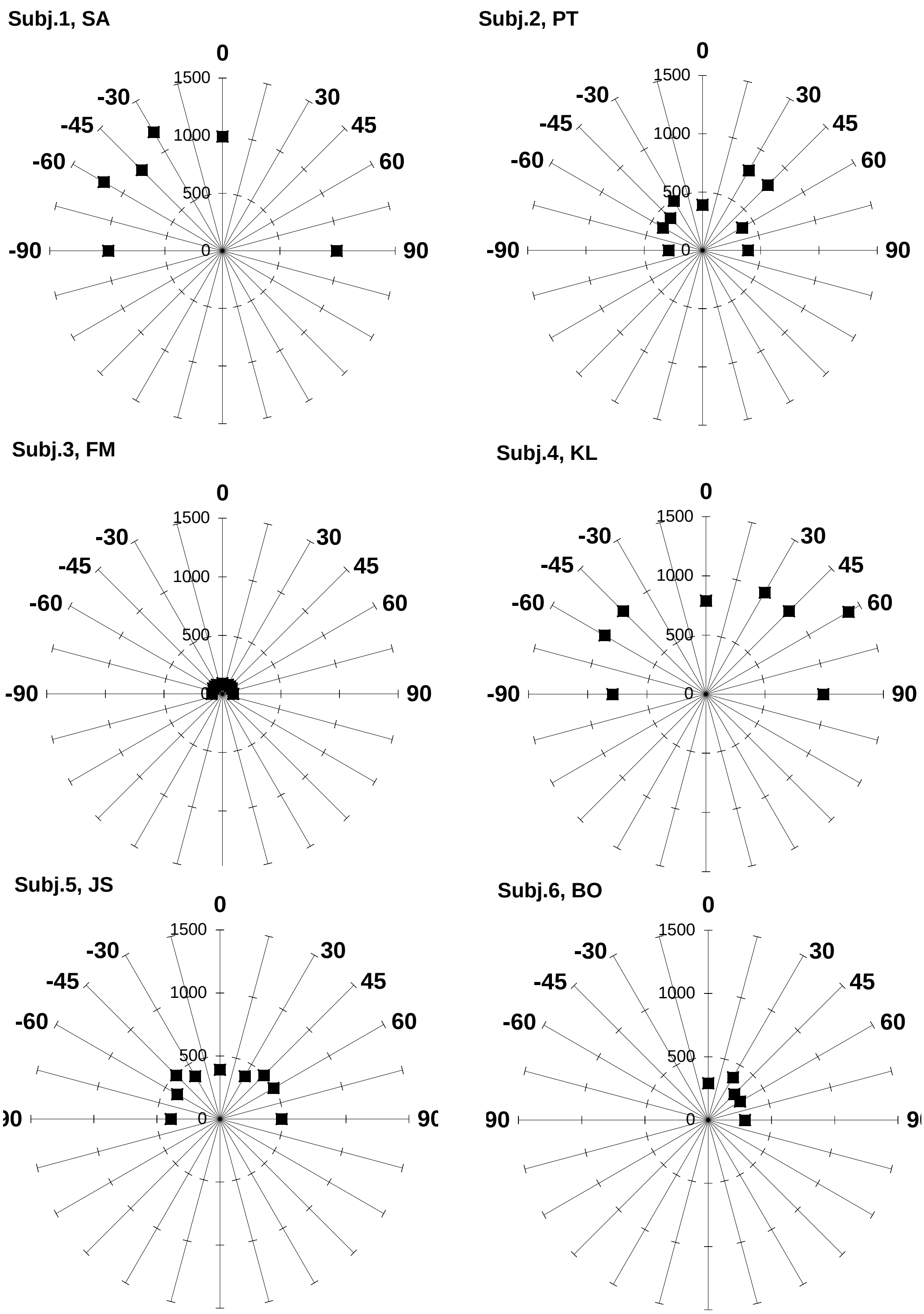
45
60
90
-30
-45
-60
-90
1500
1000
500
0

Fig.8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-30
-45
-60
-90
1500
1000
500
0

Fig.9

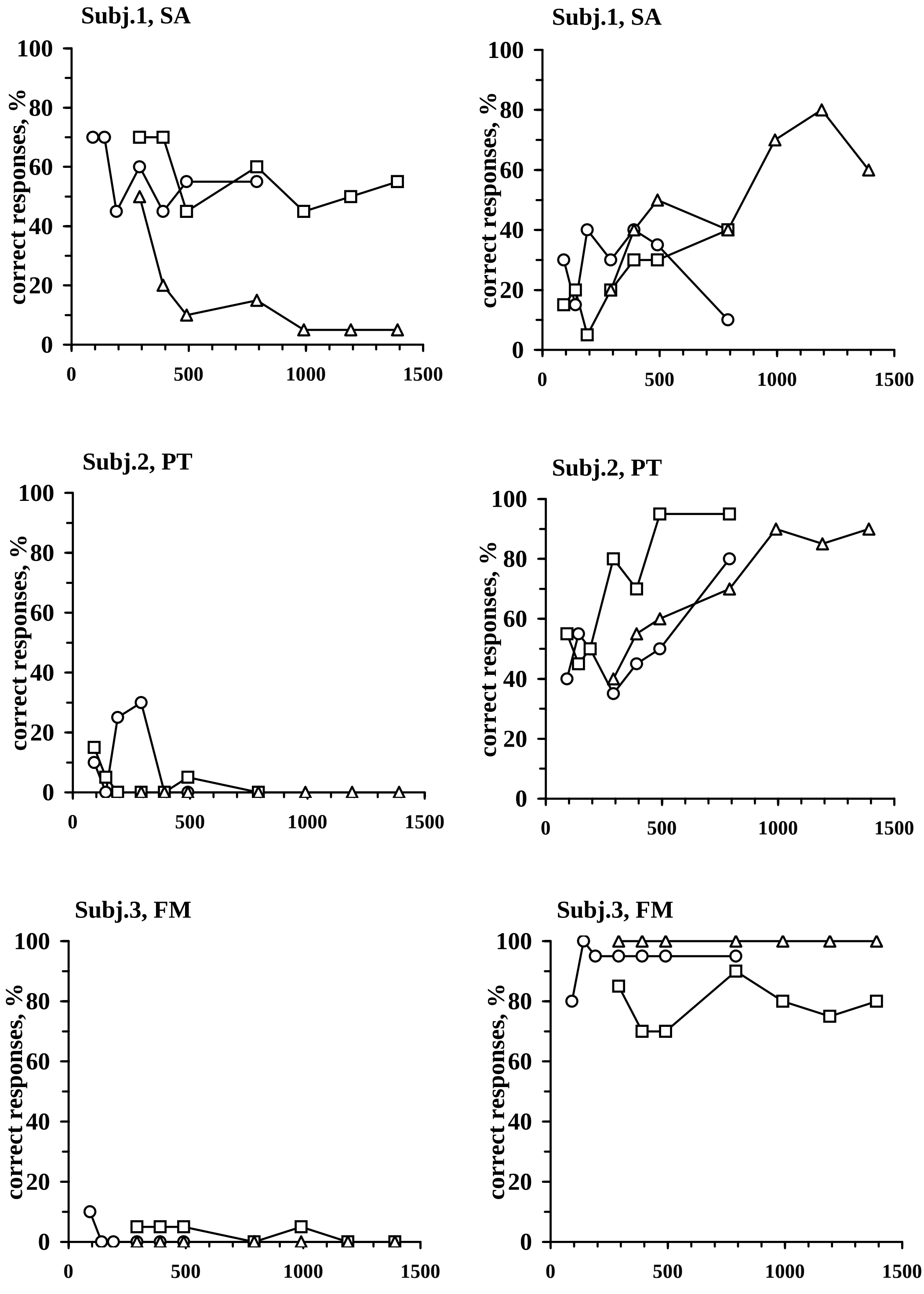

Subj.1, SA
correct responses, %
100
80
60
40
20
0
0
500
1000
1500
Subj.1, SA
Subj.2, PT
Subj.2, PT
Subj.3, FM
Subj.3, FM

Fig.10

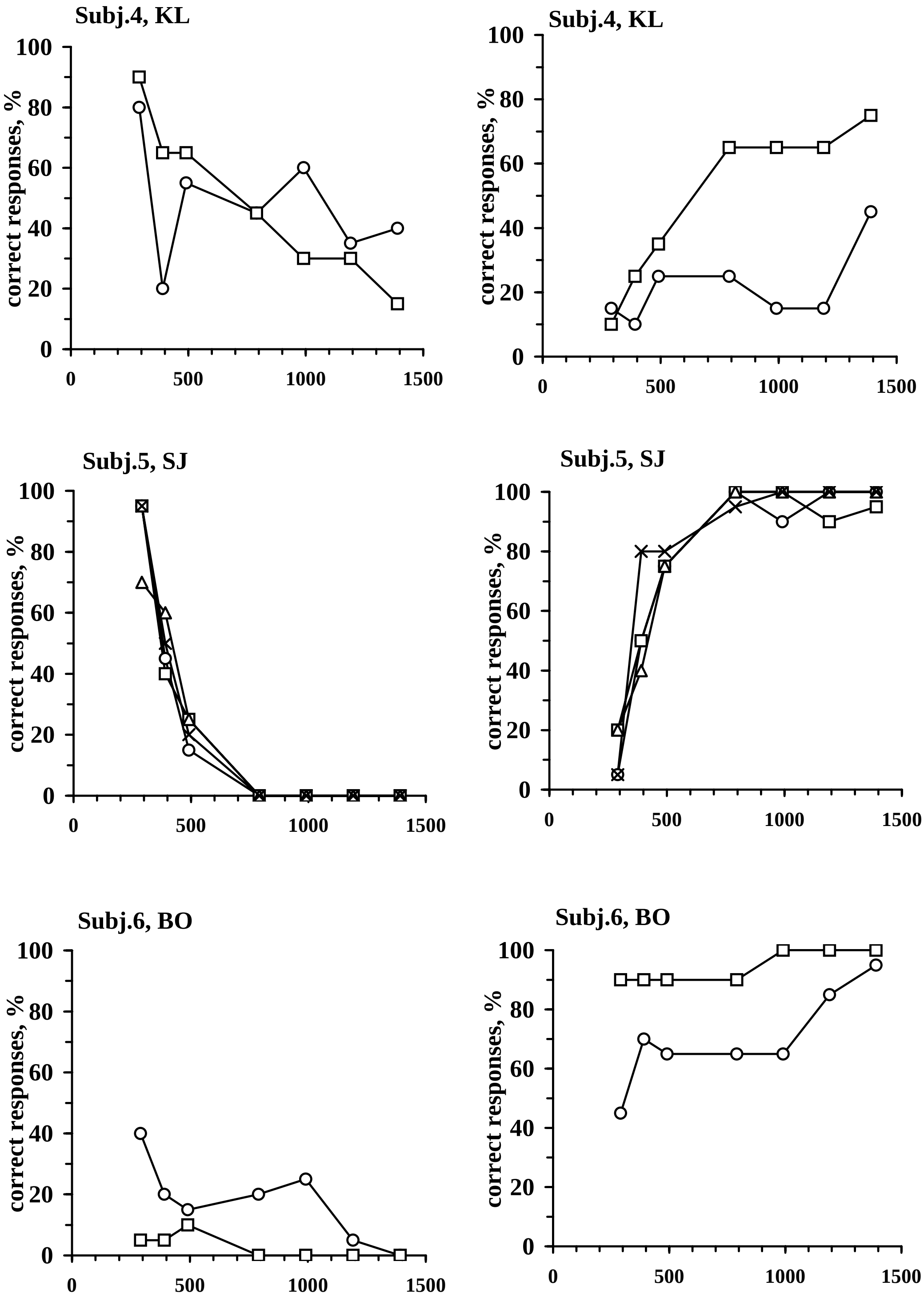
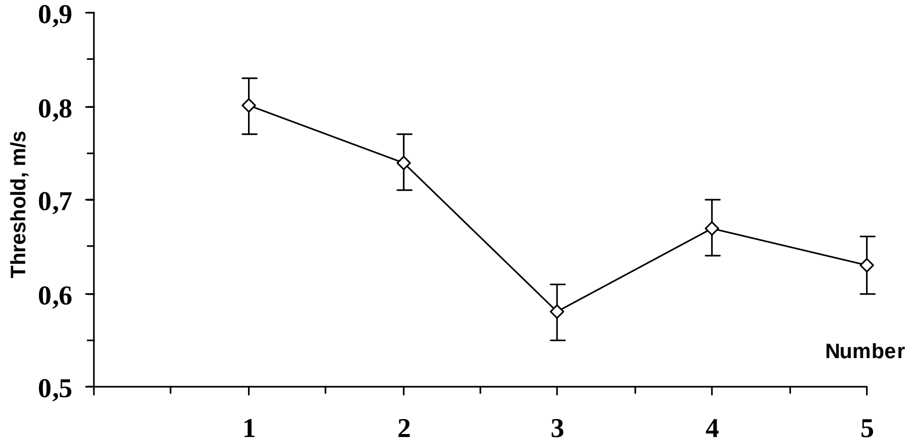

Subj.4, KL
correct responses, %
0
20
40
60
80
100
0
500
1000
1500
Subj.4, KL
correct responses, %
Subj.5, SJ
correct responses, %
Subj.5, SJ
correct responses, %
Subj.6, BO
correct responses, %
Subj.6, BO
correct responses, %

Fig.11

1


0,9
0,8
0,7
0,6
0,5
Threshold, m/s
Number
1
2
3
4
5

2

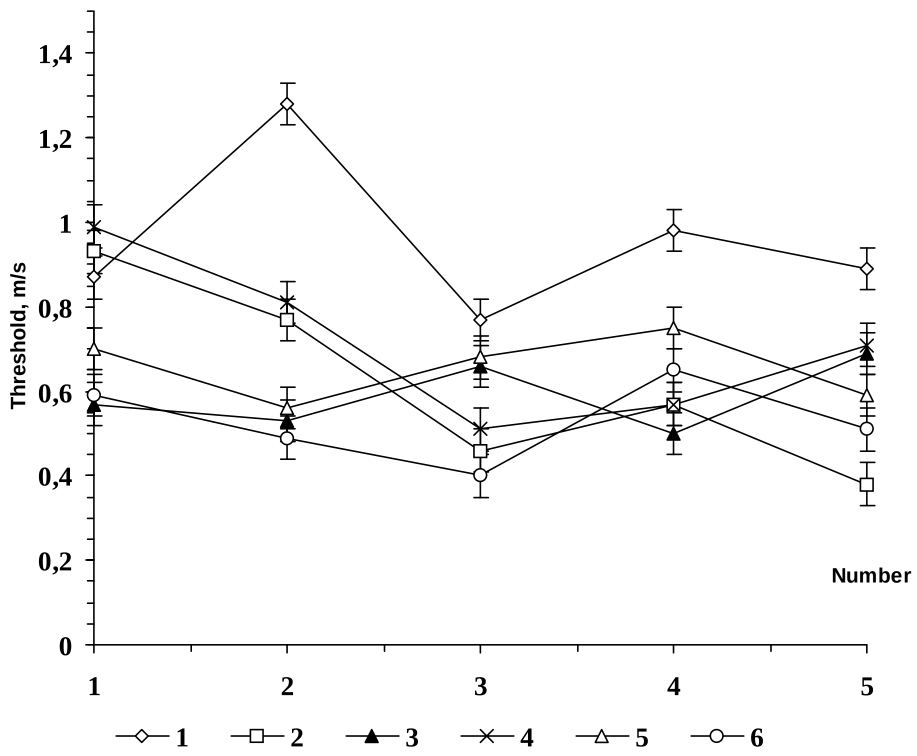

1,4
1,2
1
0,8
0,6
0,4
0,2
0
Threshold, m/s
Number
1
2
3
4
5
1
2
3
4
5
6

Fig.12

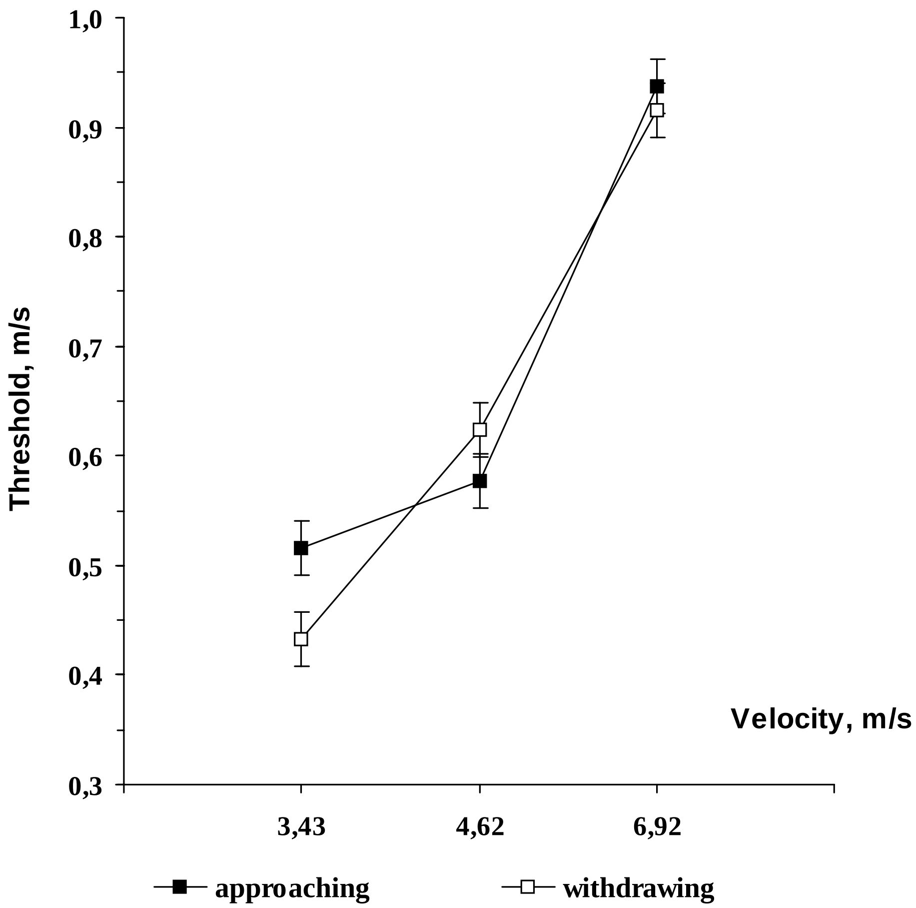
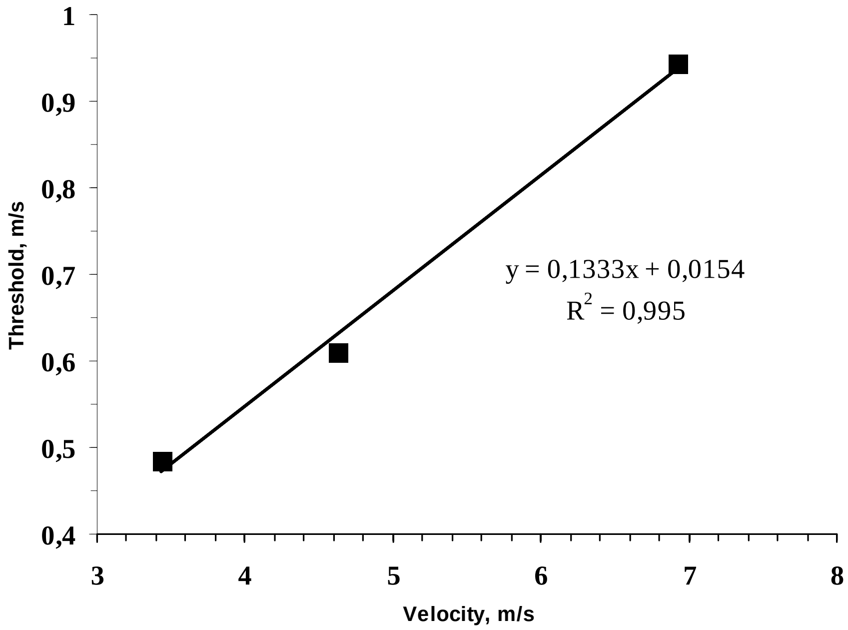

1,0
0,9
0,8
0,7
0,6
0,5
0,4
0,3
Threshold, m/s
Velocity, m/s
3,43
4,62
6,92
approaching
withdrawing

Fig.13

1


Threshold, m/s
Velocity, m/s
y = 0,1333x + 0,0154
R2 = 0,995
1
0,9
0,8
0,7
0,6
0,5
0,4
3
4
5
6
7
8

2

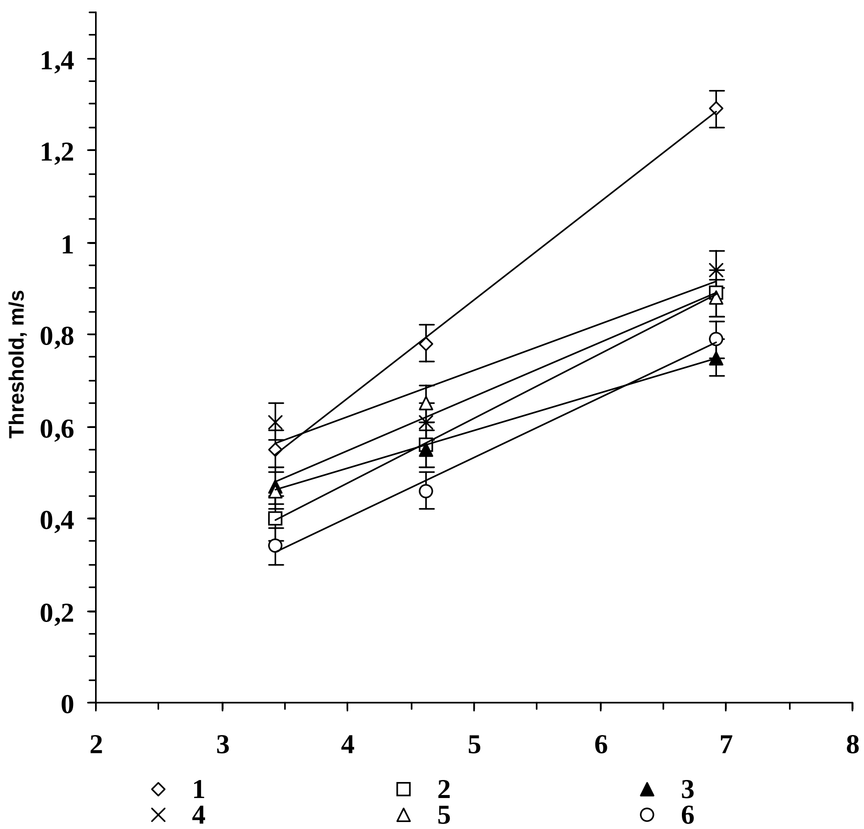
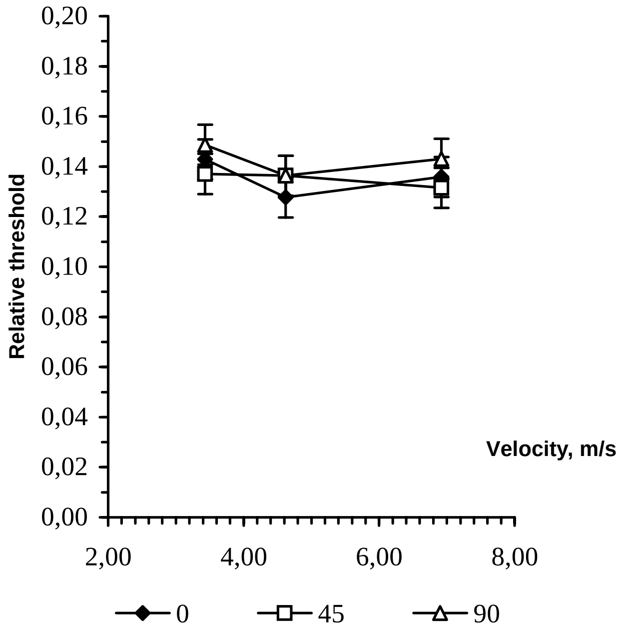

Threshold, m/s
1,4
1,2
1
0,8
0,6
0,4
0,2
0
2
3
4
5
6
7
8
1
2
3
4
5
6

Fig.14

1


0,20
0,18
0,16
0,14
0,12
0,10
0,08
0,06
0,04
0,02
0,00
Relative threshold
Velocity, m/s
2,00
4,00
6,00
8,00
0
45
90

2

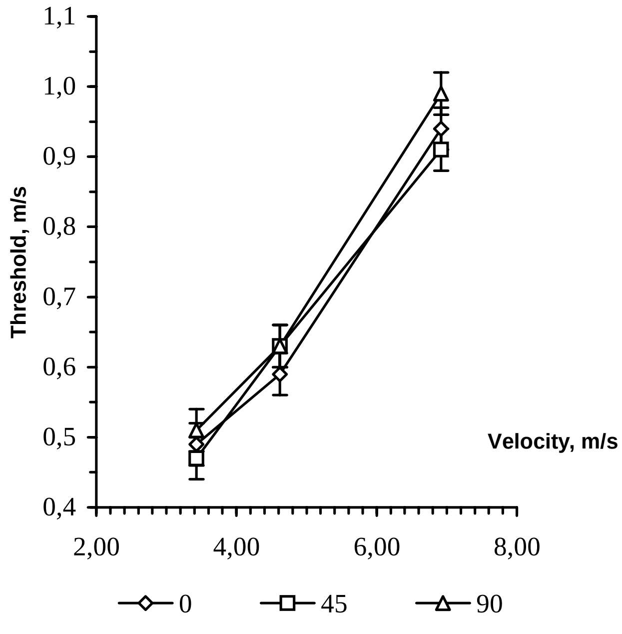

1,1
1,0
0,9
0,8
0,7
0,6
0,5
0,4
Threshold, m/s
Velocity, m/s
2,00
4,00
6,00
8,00
0
45
90

Fig.15

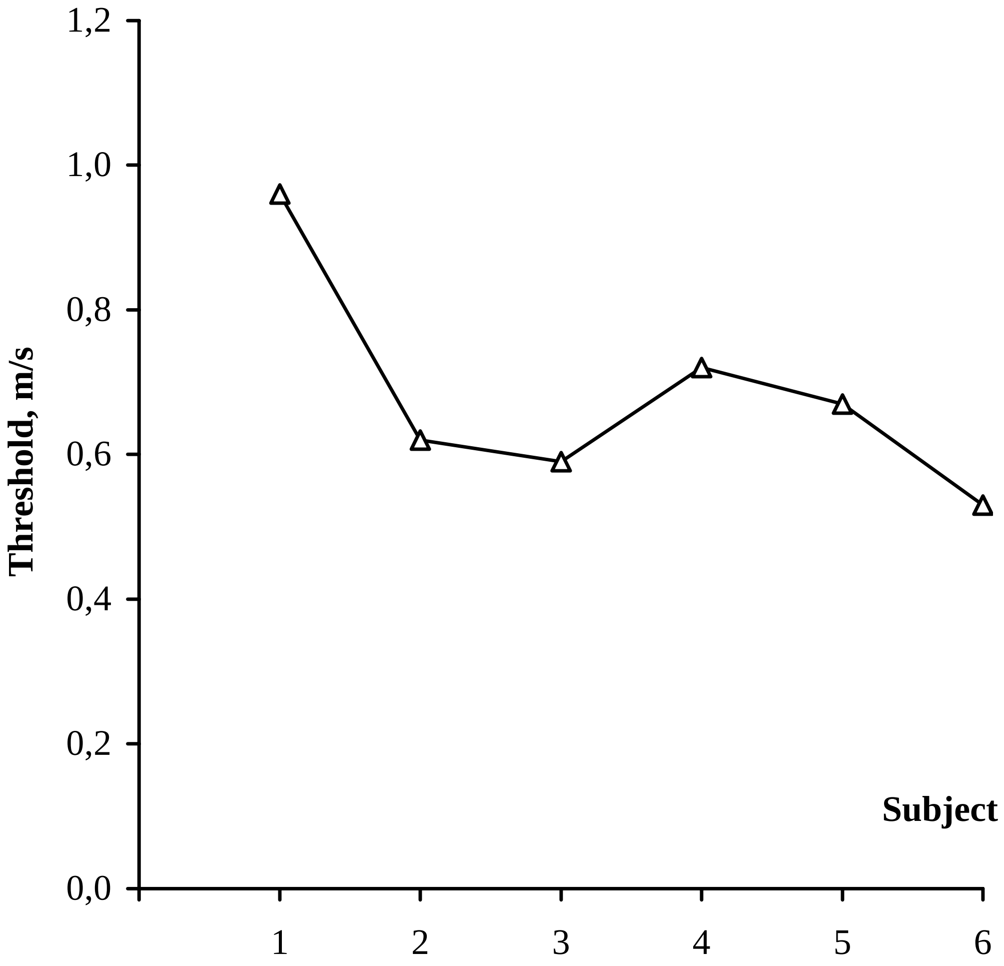


Fig.16

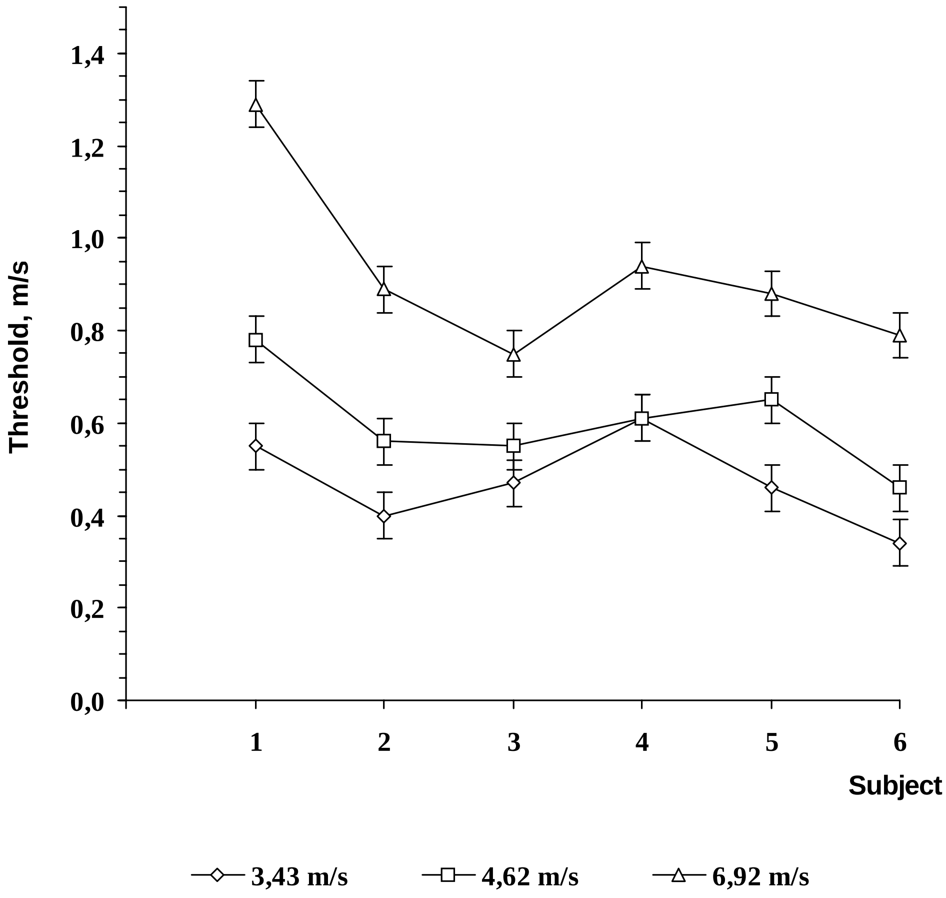

Threshold, m/s
1,4
1,2
1,0
0,8
0,6
0,4
0,2
0,0
1
2
3
4
5
6
Subject
3,43 m/s
4,62 m/s
6,92 m/s

Fig.17

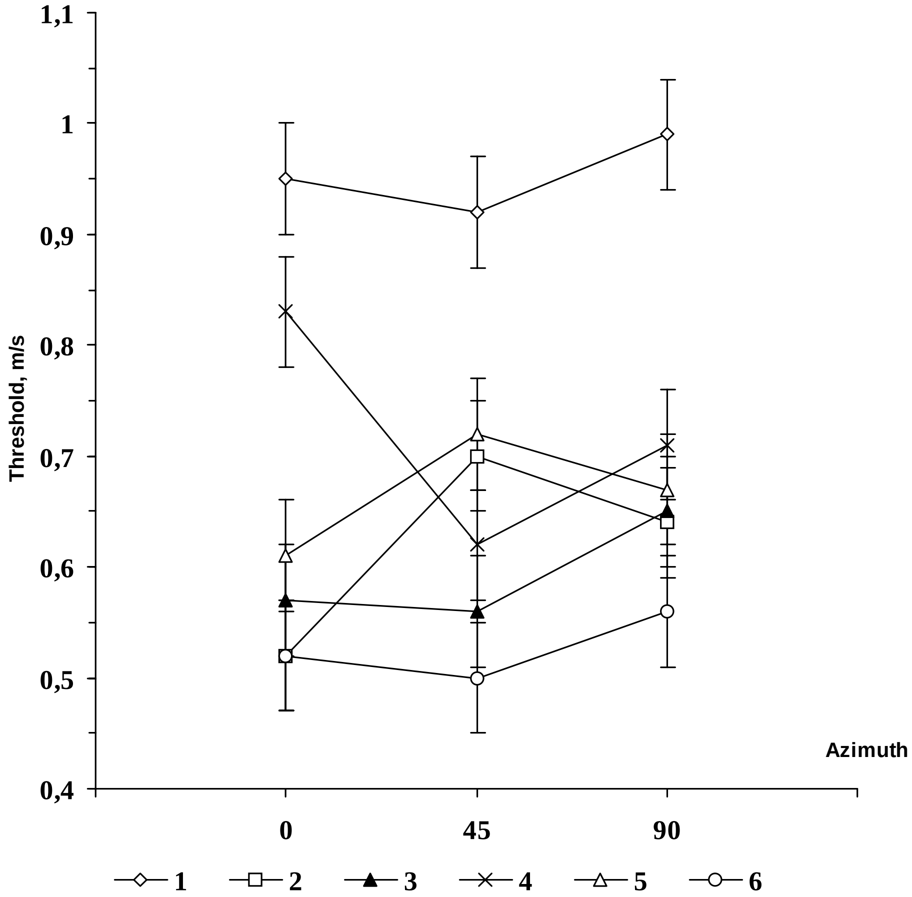


Fig.18

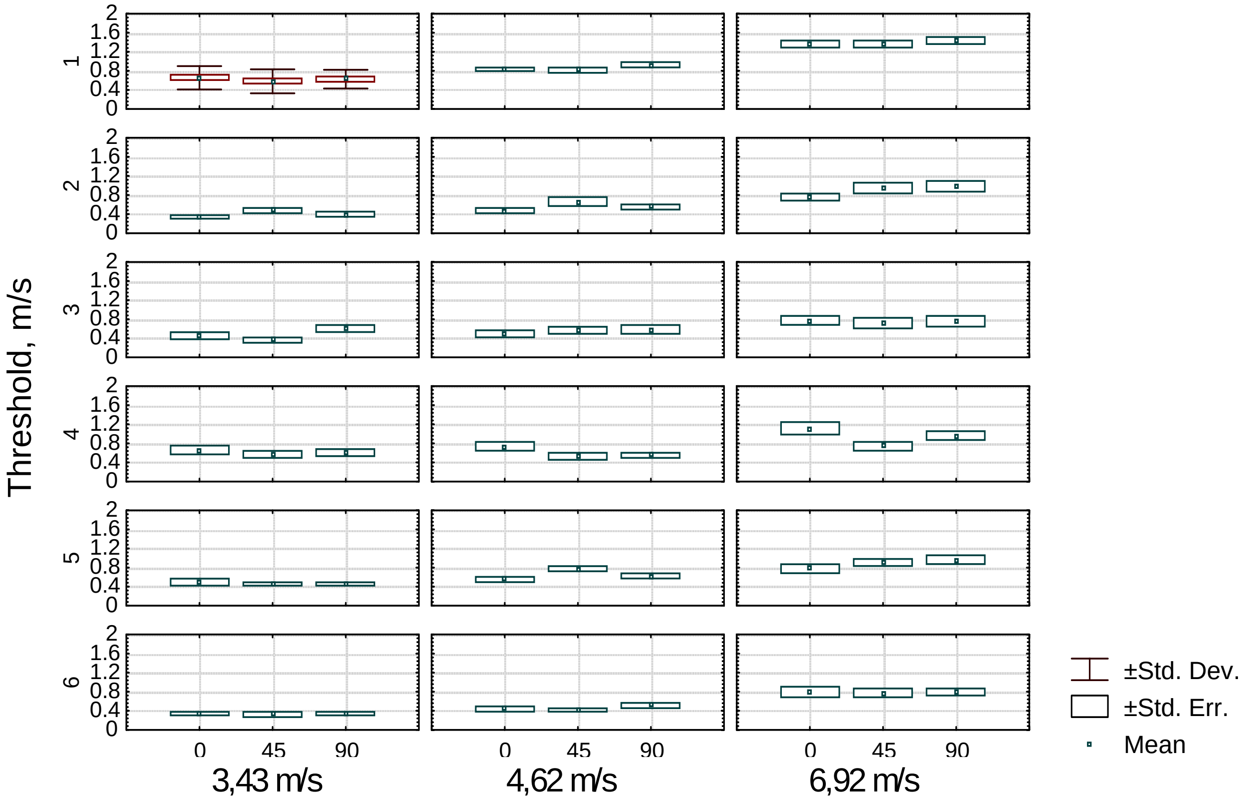
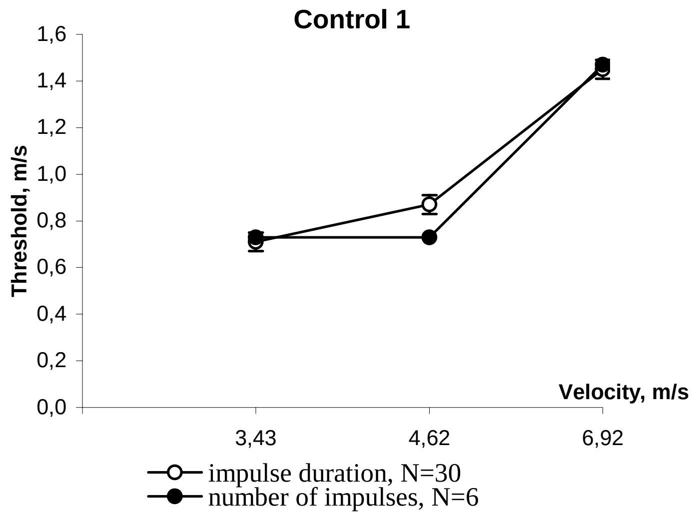

Threshold, m/s
1
2
3
4
5
6
2
1.6
1.2
0.8
0.4
0
0
45
90
3,43 m/s
4,62 m/s
6,92 m/s
±Std. Dev.
±Std. Err.
Mean

Fig.19


Control 1
Threshold, m/s
1,6
1,4
1,2
1,0
0,8
0,6
0,4
0,2
0,0
Velocity, m/s
3,43
4,62
6,92
impulse duration, N=30
number of impulses, N=6

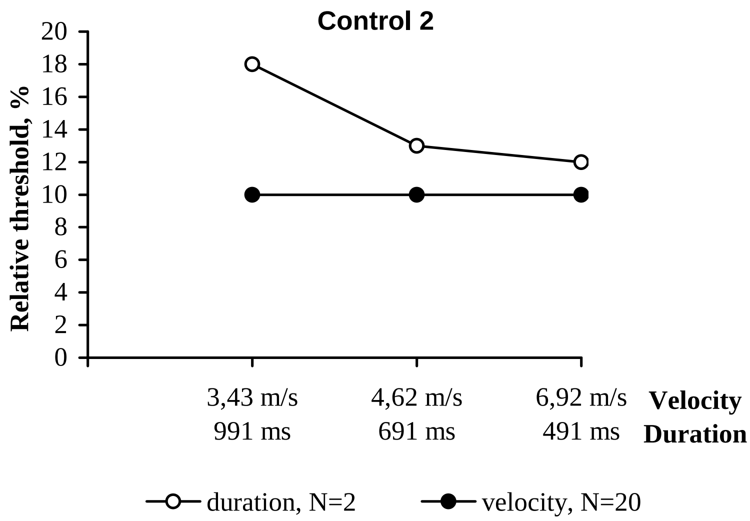

Control 2
Relative threshold, %
20
18
16
14
12
10
8
6
4
2
0
3,43 m/s
991 ms
4,62 m/s
691 ms
6,92 m/s
491 ms
Velocity
Duration
duration, N=2
velocity, N=20

Fig.20